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AFML-TR-69-119

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A SURVEY OF RATE DEPENDENT STRENGTH PROPERTIES OF METALS

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R. L. BESSEY

Southwest Research Institute

TECHNICAL REPORT AFML-TR-69-119

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FOREWORD

This report was prepared by the Department of Mechanical Sciences, Southwest Research Institute, San Antonio, Texas under USAF Contract No. AF 33(615)-5338. The contract was initiated under Project No. 7351, "Metallic Materials," Task No. 735106, "Behavior of Metals." The work was monitored by the Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, with Dr. T. Nicholas, MAMD, as project scientist.

This report presents data surveyed during the course of the contract from July 1966 to November 1968. The manuscript of this report was released by the authors March 1969 for publication.

This technical report has been reviewed and is approved.

W. J. Trapp
Chief, Strength and Dynamics Branch
Metals and Ceramics Division
Air Force Materials Laboratory

ABSTRACT

The data available from the open literature concerning the effect of strain rate on the strength properties of metals have been collected and are presented in graphical form. The range in strain rate included is from approximately 10^{-4} in/in/sec to 10^{3} in/in/sec. While most of the strength data have been obtained at room temperature, some elevated temperature data are available also. It can be seen that most information has been obtained on the aluminum and ferrous alloys.

The collection of data should serve as a useful source for those requiring high strain-rate information for design applications and as an indication where further work is required.

This abstract is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

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SECTION I

INTRODUCTION

There is an increasing demand for information concerning the strength properties of metals for applications where the expected rate of deformation is much higher than encountered in the conventional static or quasi-static tests. Applications for high deformation rate data include high speed metal working and metal forming processes, ballistic and projectile impact studies, calculations of blast response of structures, crack propagation studies, and other situations where high intensity transient loads are encountered. While the earliest studies of strength properties of metals under impact loads date back to 1914, major interest was renewed during the second world war when several significant contributions were made to the theory of inelastic wave propagation in metals simultaneously with attempts to measure strength properties at high rates. These early experimental efforts were successful primarily in showing a qualitative increase in strength properites with increasing rate of deformation. The real progress in the quantitiative measurement of strength properties at high rates has come only within the past ten years. This has come about because of the gradual evolution of appropriate dynamic test techniques, which must overcome many formidable problems, and because of the development of adequate dynamic measurement and recording instrumentation. Even so, today there are by no means standard or universally accepted test procedures or techniques for generating high deformation rate data. The available data are the result of isolated research efforts utilizing a variety of test techniques. Therefore, to a great extent, the reliability of the data is still left to the judgment of the user.

In this survey we have compiled some of the data available from the open literature in the hope that it will serve as a useful reference source for those requiring such information. Additional high strain-rate data on several commercially important alloys was generated and presented in a previous report under this project(1)*.

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* Superscript numerals in parenthesis refer to list of References, Section V.

SECTION II

SUMMARY OF TEST TECHNIQUES

The data presented generally cover a range in strain rate from approximately 10^{-4} in/in/sec to 1000 in/in/sec. The lower rates are thus accessible to conventional quasi-static testing machines. Since interpretation of this data does not involve considerations of dynamic or inertial effects, the strength properties at these lower rates serve as a reference for the high rate data. In order to cover the entire range of the higher strain rates, usually two additional types of testing devices are needed. In the range from 0.1 in/in/sec to 100 in/in/sec the loading is supplied either by fast-acting mechanical devices (a large moving mass or rotating flywheel) or by pneumatically or hydraulically driven piston devices. At rates of the order of 1000 in/in/sec the loading is usually generated by high velocity impact coupled to the specimen by means of long elastic pressure bars. Less widely used at the higher rates are "ring" type tests which will also be referenced in the following discussion.

The above-mentioned test techniques all employ what we may call "contained" plastic deformation. That is, the plastic deformation is contained within a small, but finite size specimen, and it is assumed that the variables of stress and strain are uniform throughout the contained volume. Measurements of the applied loads and the relative displacements across the specimen then yield the <u>average</u> stress and strain within the contained element or specimen. In this respect these tests are extensions of the conventional quasi-static test to higher effective crosshead velocities. An alternate, and basically different test technique, sometimes used to determine material strength properties, involves measurement of "uncontained" or "free-running" deformation in the form of plastic stress waves. The two most useful tests of this type involve longitudinal impact of long rods (uniaxial stress) and the transverse impact of thin plates (uniaxial strain). In these tests the stress, strain and strain rate vary continuously in both space and time. The shape of the propagating wave profiles reflect the form of the stress-strain relation. However, it is difficult to extract a <u>unique</u> consitutive relationship from the wave profile data since only a deformation parameter(strain or particle velocity) is measured at each point. Stress must be derived from solving the governing partial differential equations in conjunction with an assumed form of constitutive relation. In the writers' opinion, the wave propagation test is most useful with regard to determining inelastic material properties, when used to verify assumed or otherwise measured constitutive relations. This statement becomes qualified at rates above 10^4 in/in/sec where the plate impact experiment becomes essentially the only tool we have to get at strength properties.

The remaining paragraphs of this section will discuss briefly those techniques employed in generating the high strain rate data presented. The reader is referred to the references cited for more detailed information. The supplementary references in Section V include books, proceedings, and review articles related to the subject.

In the intermediate strain-rate range, test systems may be divided into mechanical or pneumatic/hydraulic based upon the mechanism of loading. Mechanical systems were some of the first to be used. Mechanical energy is stored in a gravity-accelerated mass (pendulum or drop-weight) or in a rotating flywheel. When the appropriate velocity is reached, the moving mass is suddenly coupled to the specimen which absorbes the kinetic energy through deformation. Constant rate of deformation is achieved only if the initial kinetic energy is large compared to the work required to deform the specimen. Pendulum type machines are described by Clark and Datwyler(2), and Mann(3). Manjoine and Nadai(4, 5) constructed a machine employing a rotating flywheel and were among the first to instrument to give continuous stress-strain curves. A disadvantage of the preceding devices is that in the sudden coupling of the moving mass to the specimen and series connected load cell configuration, serious elastic oscillations may be set up at the resonant frequency of the system. Orowan(6), Alder and Phillips(7), and more recently Hockett(8) have used the rotating flywheel concept in conjunction with what is called a cam plastometer. In this device, when the flywheel is up to speed, it is coupled to the specimen through a logarithmically contoured cam and cam follower. This technique avoids the sudded impact and provides a constant true strain rate if the rotational speed of the flywheel is maintained constant. The latter requires large energy to be stored in the flywheel and, therefore, a massive system.

The second type of intermediate rate machine derives its energy from a compressed gas or fluid driving a piston. Gas driven machines are more common for the higher speeds because of the lower inertia of the working fluid. Machines of this type have been developed by Clark and Wood(9), Campbell and Marsh(10), Maiden and Green(11) and Lindholm and Yeakley(12). Hydraulic machines are inherently stiffer and more amenable to active feedback control of the system. The advent of high speed servo-valves will make the electro-hydraulic machine very attractive in the future for intermediate rate testing. Present pneumatic machines use fast-acting valves or rupture diaphragms in conjunction with controlled orifice plates to meter the flow rate and thereby control the piston or crosshead speed.

At the intermediate rates, wave propagation effects are neglected, both in the specimen and in the elastic force measuring elements in series with the specimen. The elastic elements are made as short and stiff as possible

in order to maximize the resonant frequency of the system. Various standard techniques are employed to measure relative crosshead velocity or displacement.

At rates above 100 in/in/sec, wave propagation effects have to be considered both in the measuring system and in the specimen. The most common technique in use today is the Hopkinson split pressure bar, first introduced by Kolsky[13]. Among other, Davies and Hunter[14], Lindholm[15], and Hauser[16] have utilized and modified the technique. A short specimen of the material to be tested is placed between two long cylindrical elastic pressure bars. The pressure bars transmit an impact load to the specimen. They are of sufficient length to allow recording of the complete history of the impact and the loading of the specimen by measurement of the elastic stress pulses propagated in each bar. The pulses are usually monitored by means of strain gages on the radial surfaces of the bars. Since the bars remain elastic, by applying one-dimensional elastic wave propagation theory, the strain measurements are sufficient to determine the displacement, velocity, and force on each face of the specimen. When the specimen length is short compared with the duration of the loading pulse, it can be shown that an equilibrium condition is approached in the specimen, i.e., the internal stress field is nearly uniform. Therefore, the pressure bar measurements can provide the average stress, strain and strain rate within the specimen.

While conceptually simple, the split pressure bar technique needs to be used with some care and its limitations realized. Some criticism of the technique has been presented by Conn[17] and Bell[18].

An alternate method at high rates is the expanding ring test. This test uses the symmetric expansion of a thin ring so as to obtain a uniform state of hoop tension. Since the ring is thin in the radial direction, wave propagation effects are minimized. Explosive techniques have been used to expand the ring by Johnson, et al.[19] and Hogatt, et al.[20]. Niordsen[21] has used an electromagnetic technique. At present these techniques are in the development stage and little data in the form of stress-strain curves have been obtained with them.

SECTION III

PRESENTATION OF STRAIN-RATE DATA

The data presented are relatively comprehensive but not exhaustive. We have primarily selected data for which the yield stress or the flow stress at constant strain amplitude was measured over an appreciable portion of the strain-rate range surveyed. In most cases the test produced complete stress-strain curves with strain rate as a parameter. The data are presented here in the form of plots of flow stress vs. log strain rate with strain as a parameter. This form most clearly shows the relative effect of strain rate upon flow stress. Each figure contains information regarding 1) the material, 2) source of the information (with reference number in bracket), 3) method by which data was obtained, 4) mode of deformation (tension, compression or shear), and 5) temperature at which test was performed. For more detailed information on any of the data the user should refer to the original source.

The data are arranged in the following order:

Figures 1 - 13	Aluminum alloys
Figures 14 - 17	Other fcc metals (copper and lead)
Figure 18	Summary plot of fcc metals
Figures 19 - 32	Iron and ferrous alloys
Figures 33 - 35	Titanium alloys and beryllium

The data of Figure 18 summarize the fcc metals from the large number of sources indicated in Table I. The data are presented in a form similar to that used by Holt, et al.[22] for aluminum alloys only. It can be seen from Figures 1 through 17 that the relationship between stress and log strain rate is linear over a wide range in rate. The rate sensitivity parameter is taken as the slope of this linear region, $\Delta\sigma / \Delta \log \dot{\epsilon}$, divided by a mean stress which is here defined as the stress amplitude at unit strain rate. If this parameter is multiplied by 100, it gives the percent increase in stress per decade increase in strain rate. It is evident that with increasing mean stress, due to either alloying or in some cases heat treatment in the aluminum alloys, the rate sensitivity decreases.

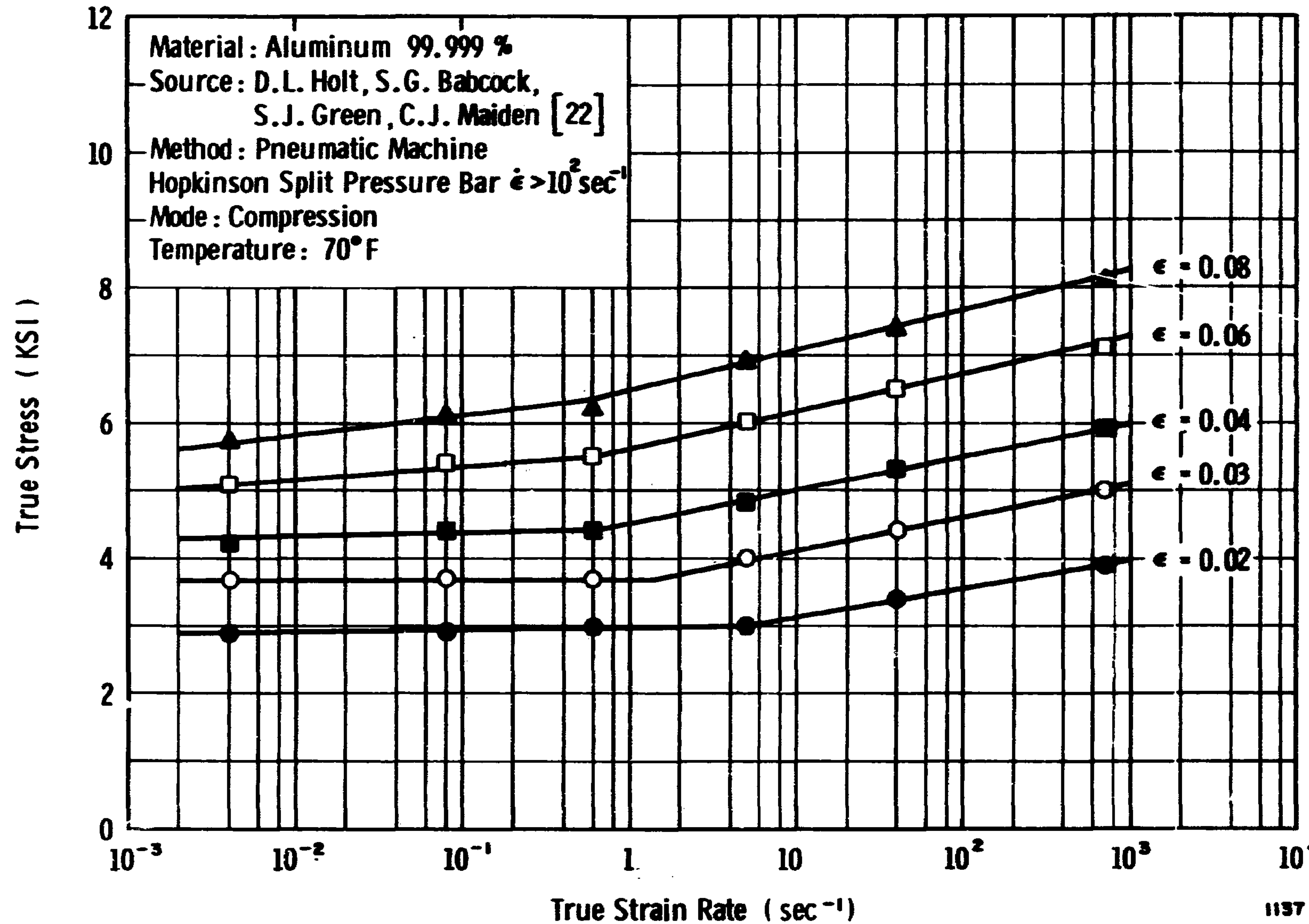

FIGURE 1. HIGH PURITY ALUMINUM

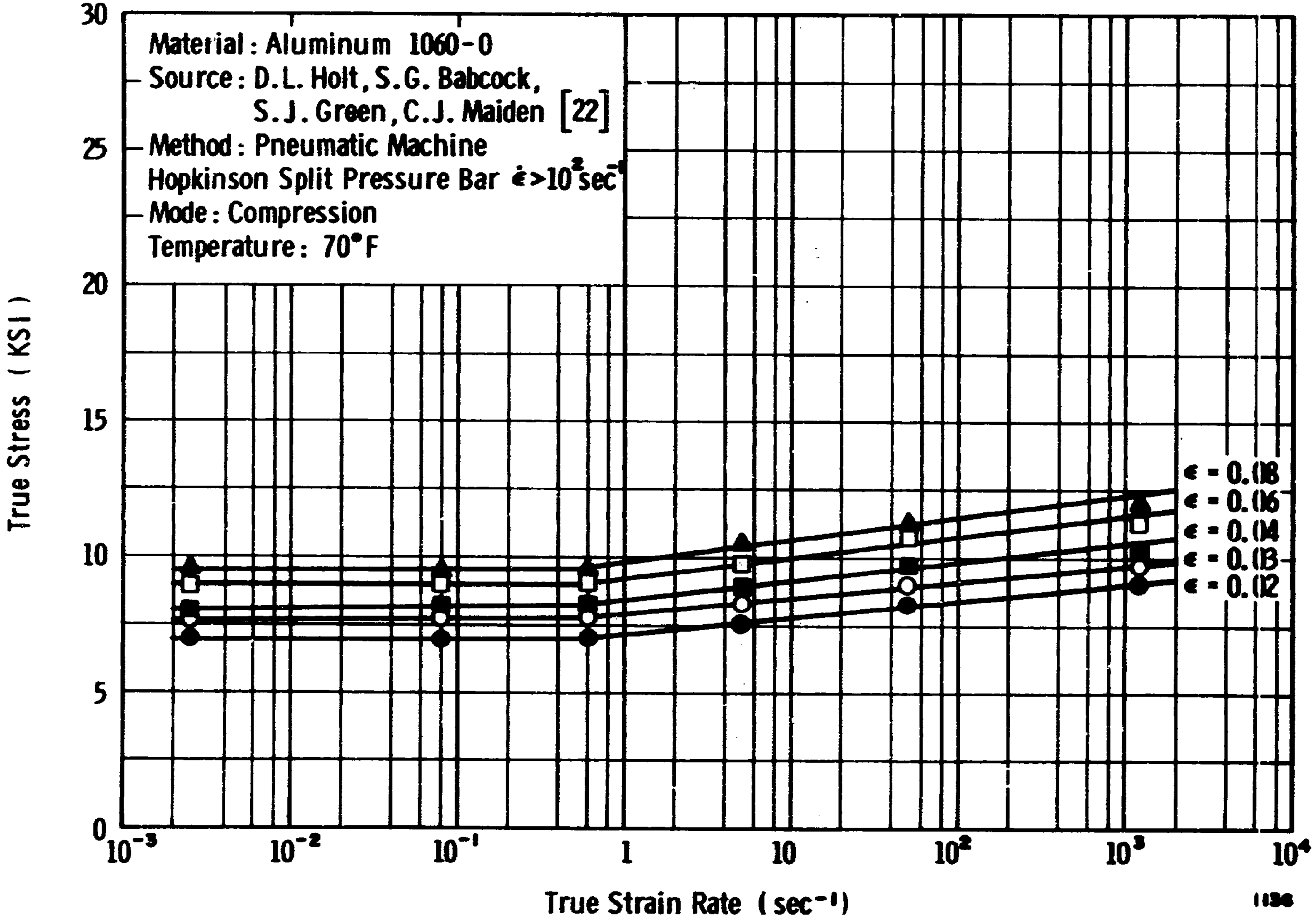

FIGURE 2. ALUMINUM ALLOY 1060-0

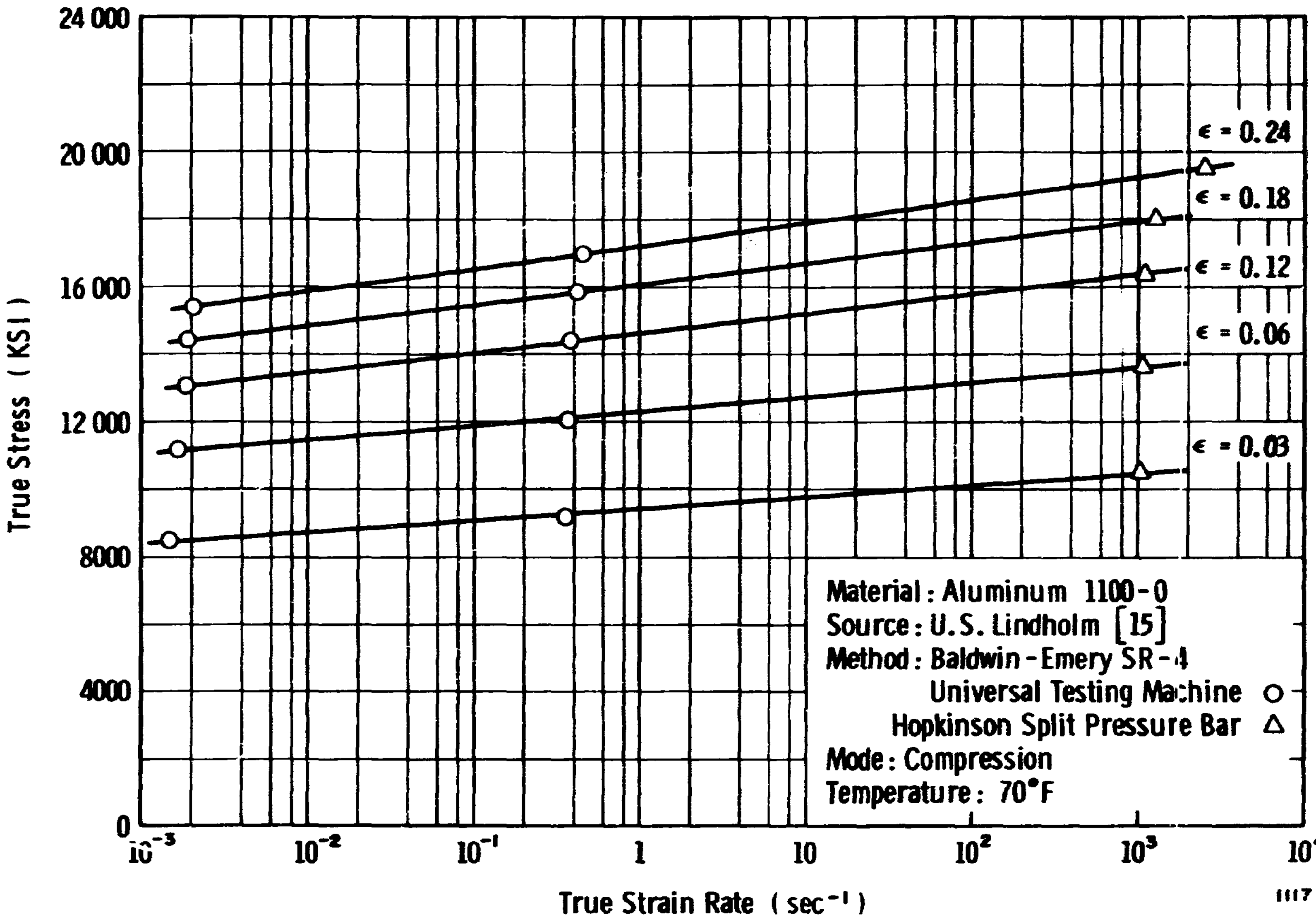

FIGURE 3. ALUMINUM ALLOY 1100-0

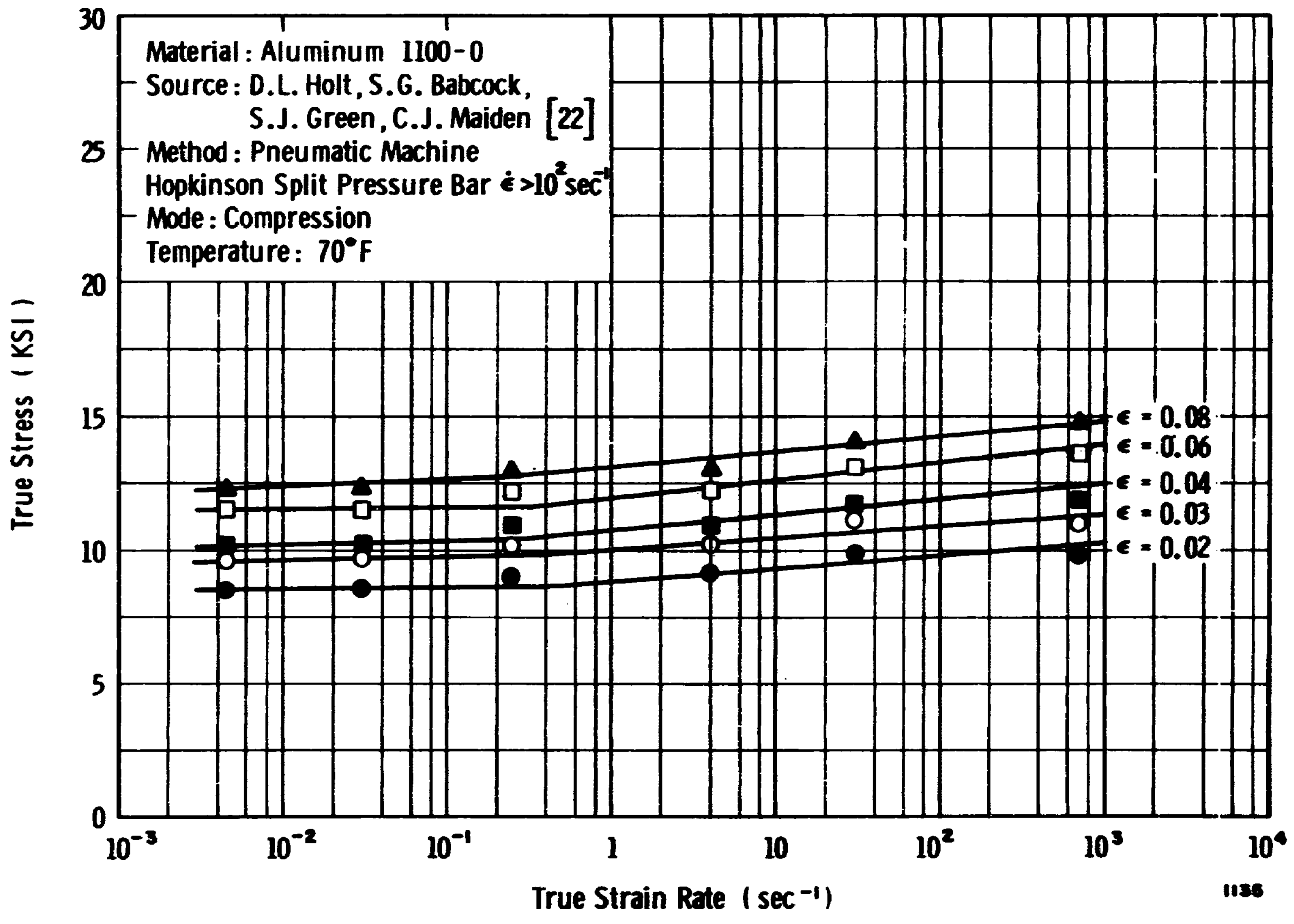

FIGURE 4. ALUMINUM ALLOY 1100-0

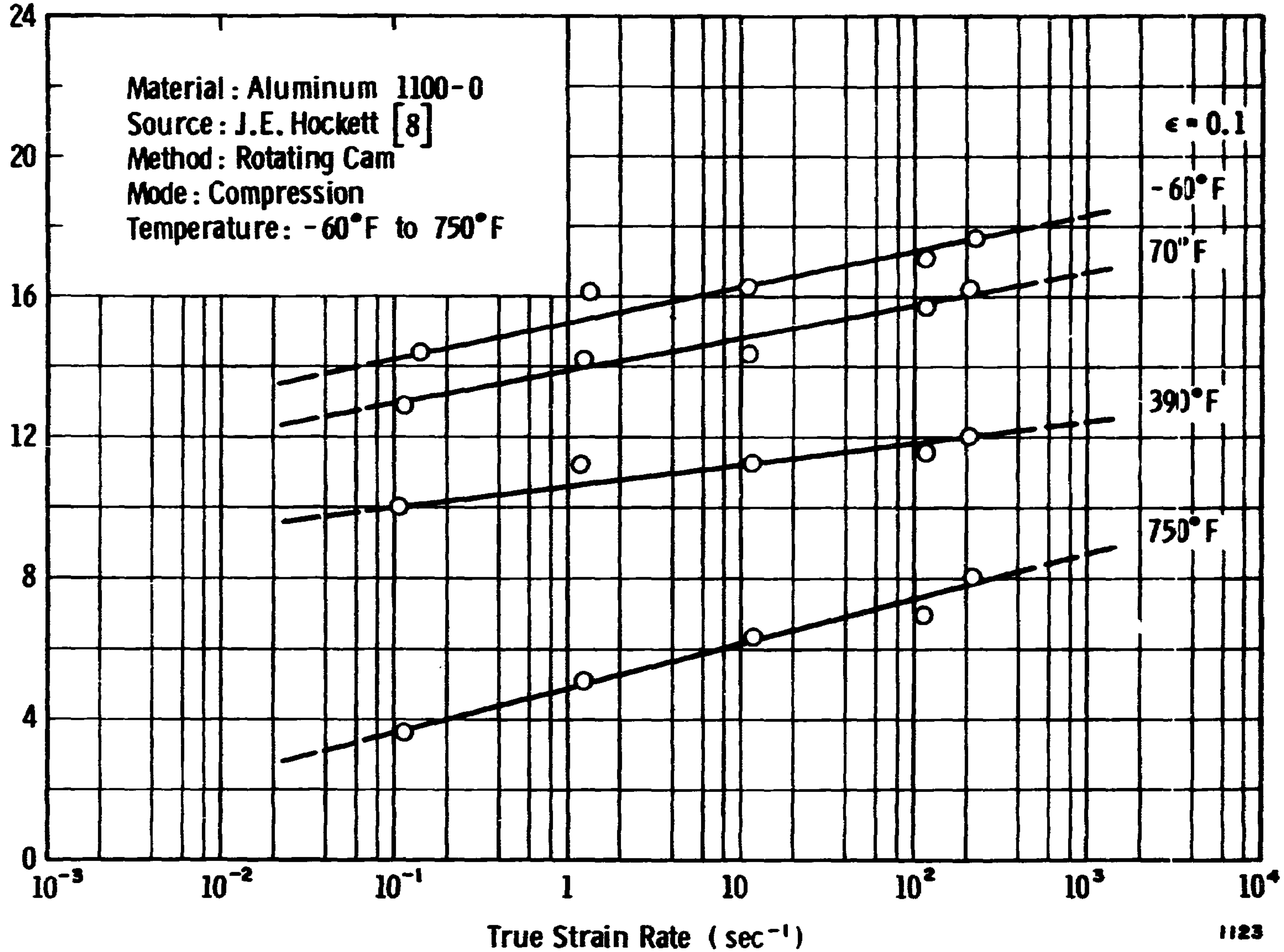

FIGURE 5. ALUMINUM ALLOY 1100-0

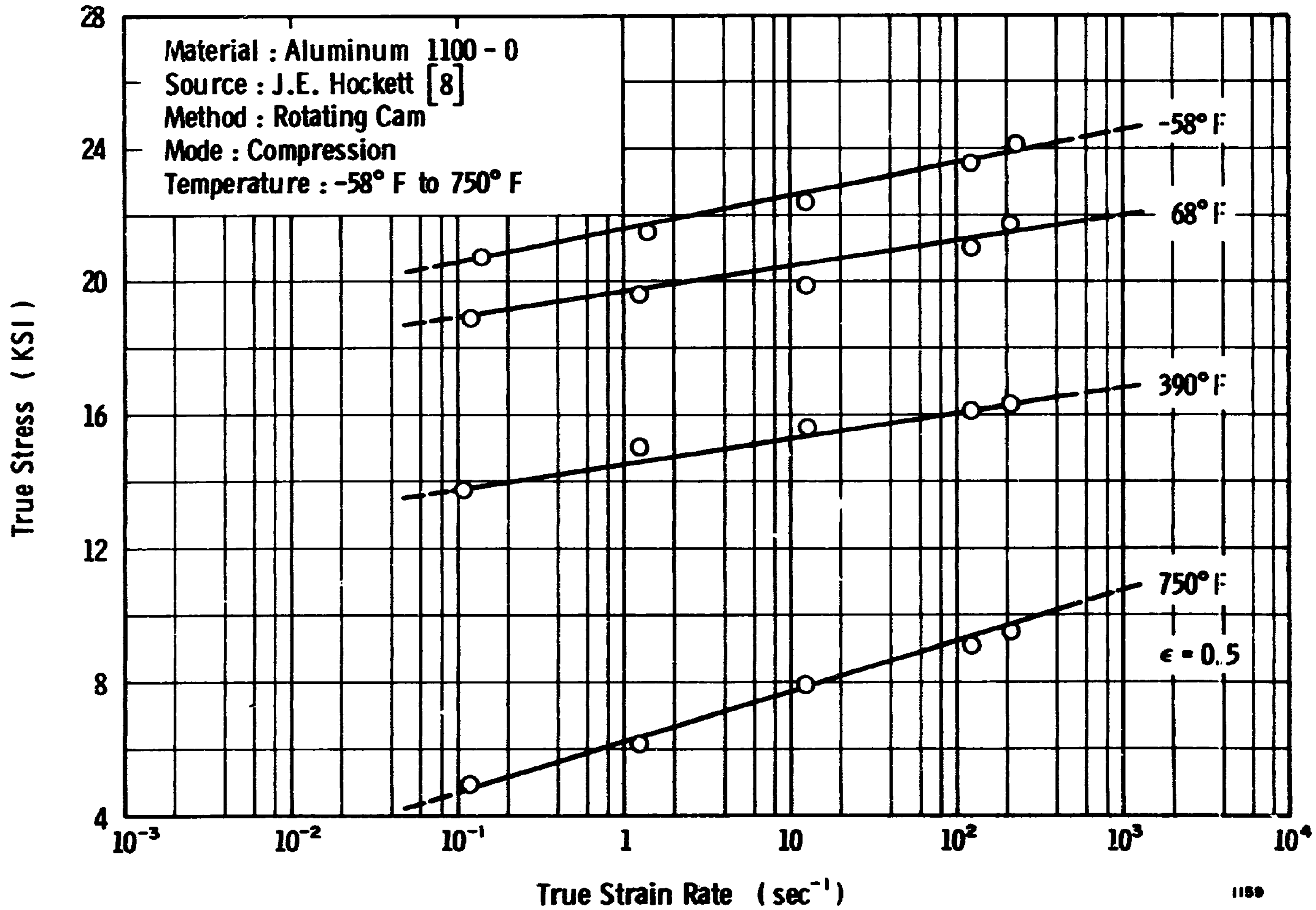

FIGURE 6. ALUMINUM ALLOY 1100-0

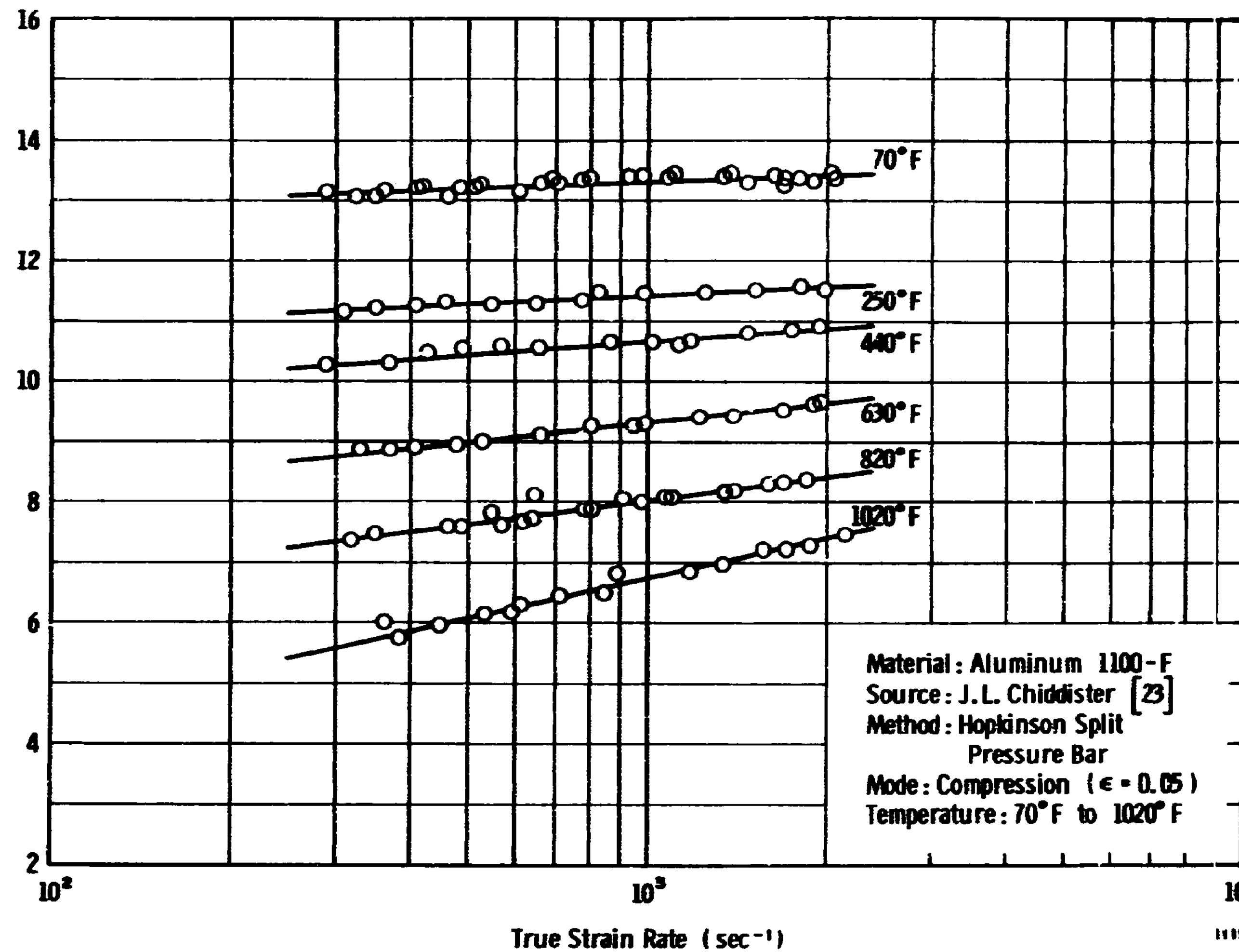

FIGURE 7. ALUMINUM ALLOY 1100-F

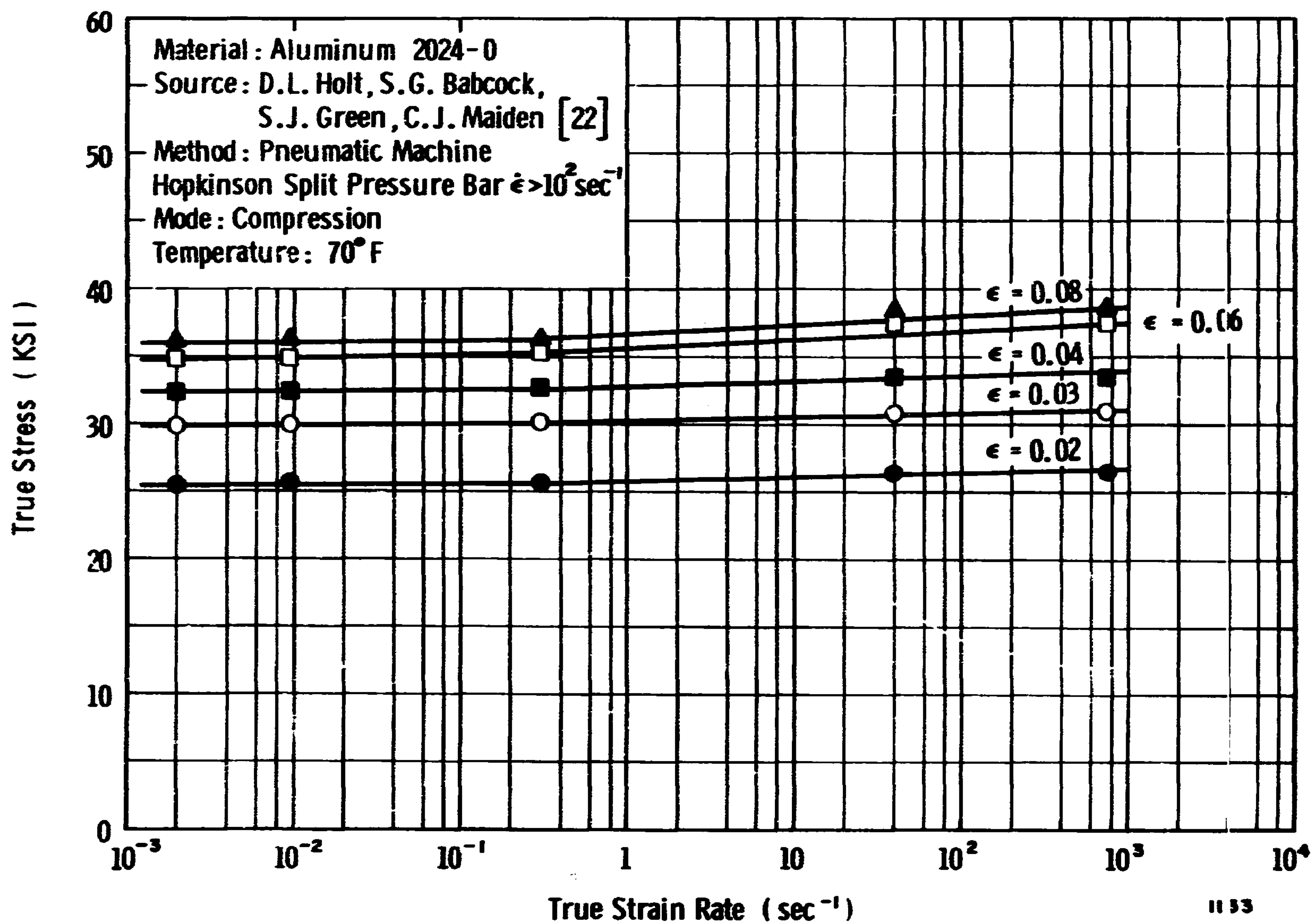

FIGURE 8. ALUMINUM ALLOY 2024-0

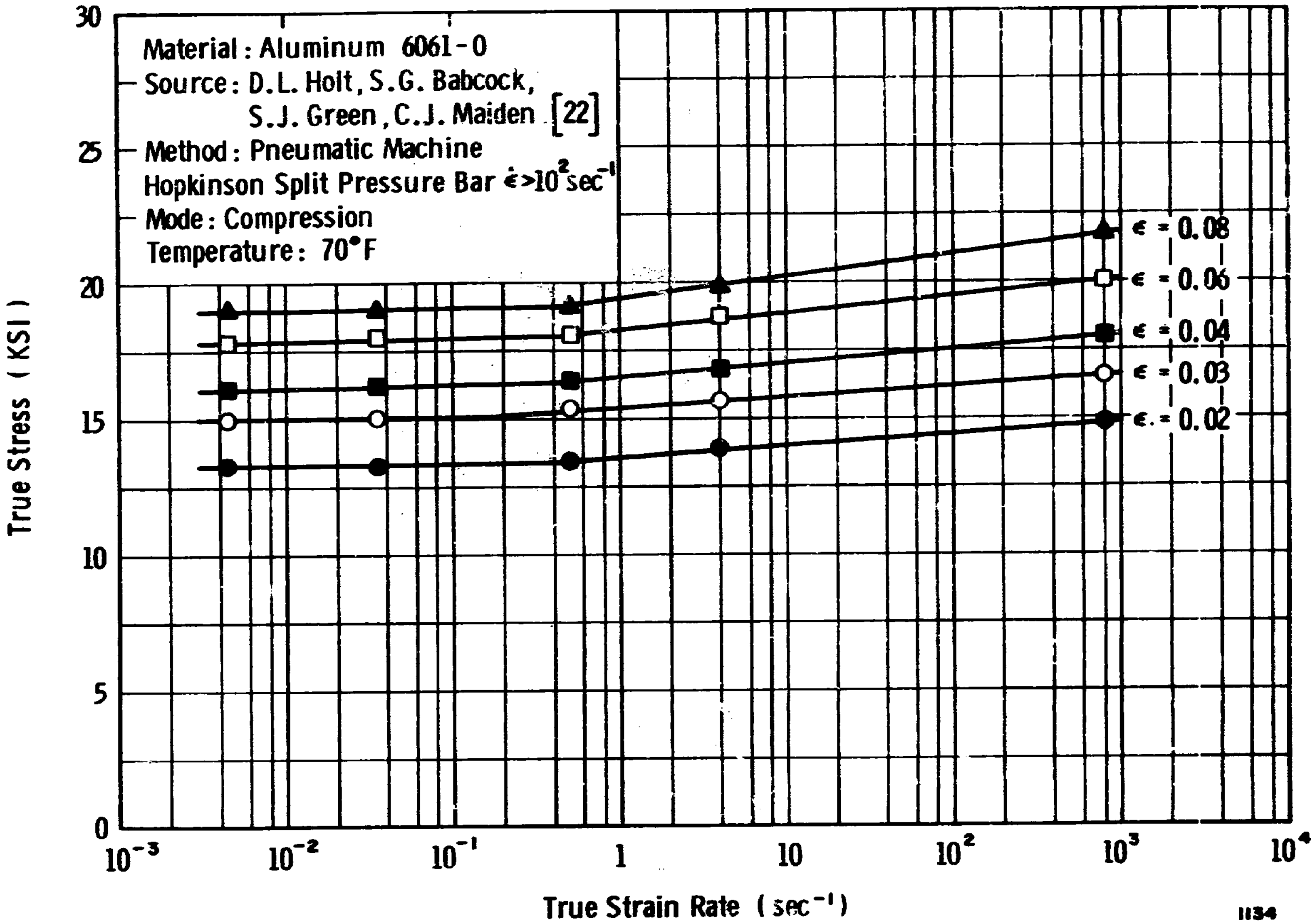

FIGURE 9. ALUMINUM ALLOY 6061-0

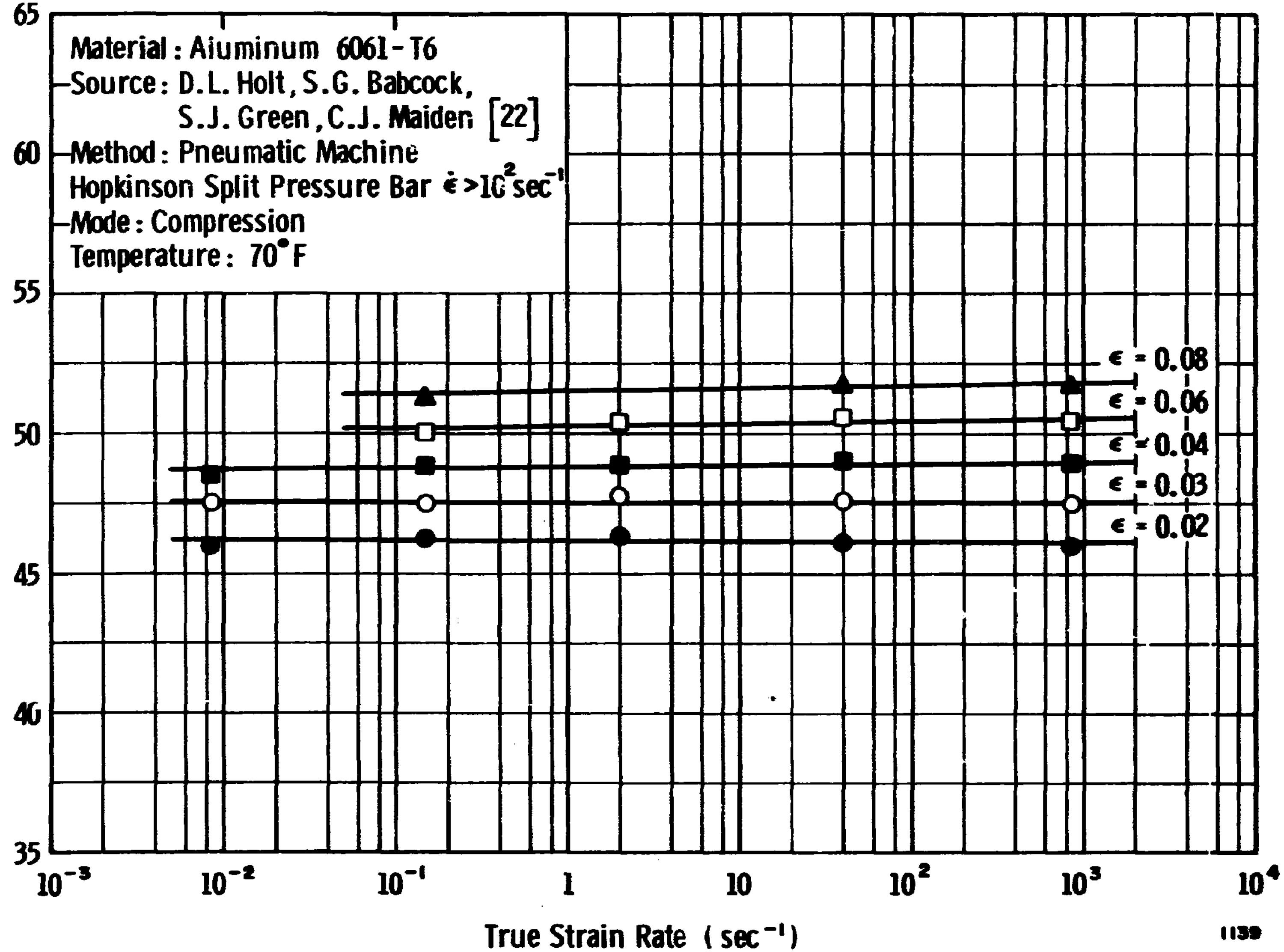

FIGURE 10. ALUMINUM ALLOY 6061-T6

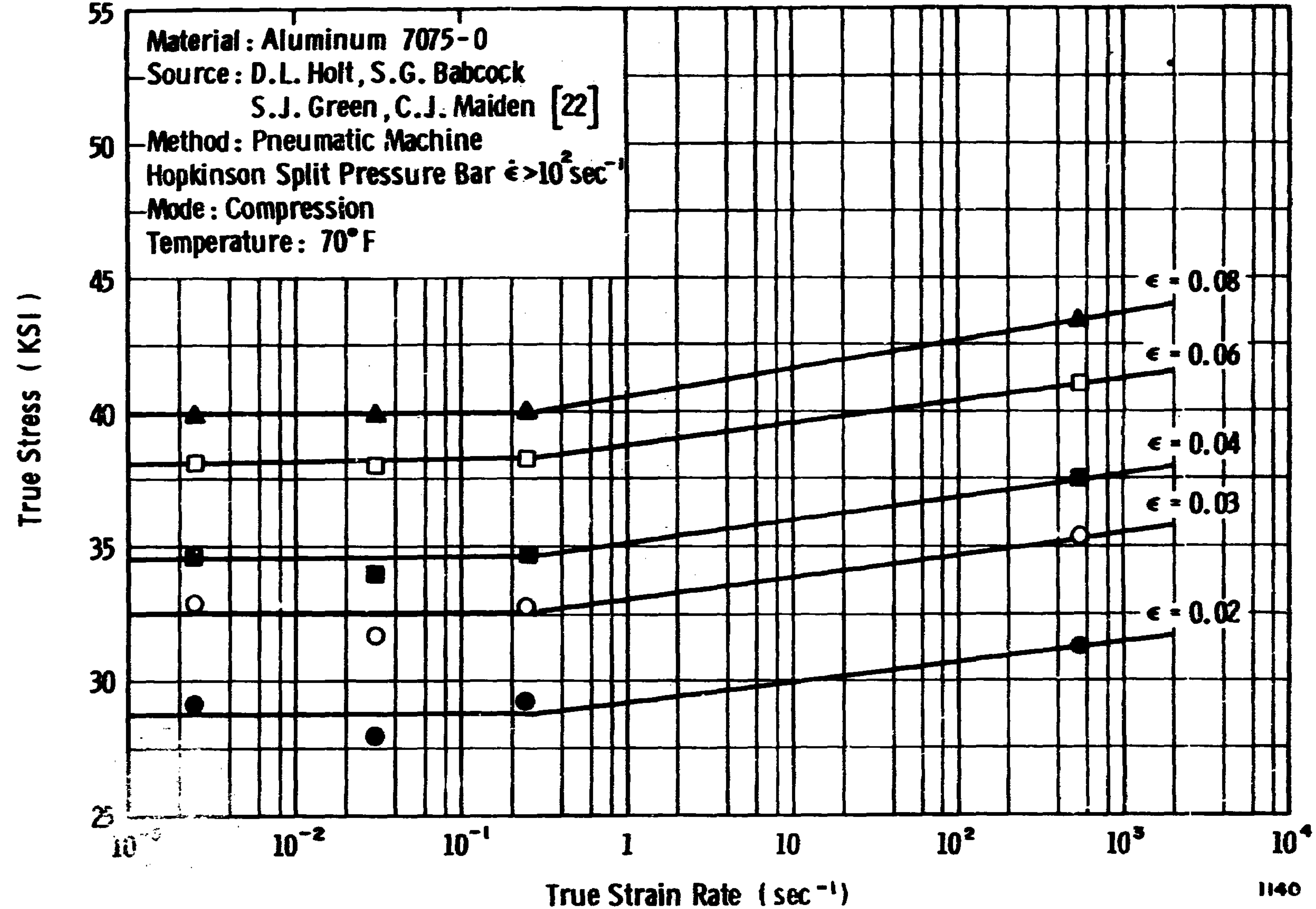

FIGURE 11. ALUMINUM ALLOY 7075-0

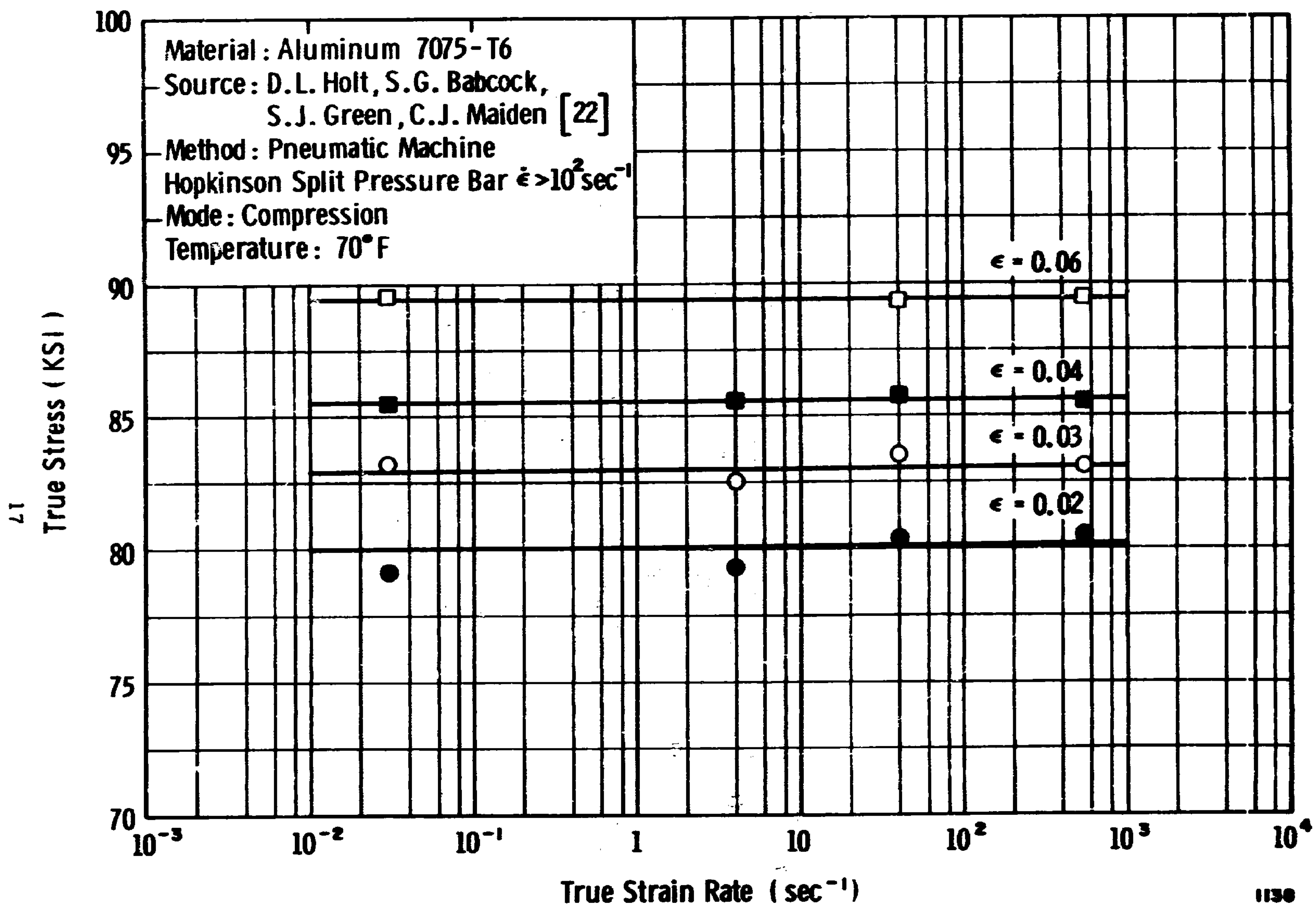

FIGURE 12. ALUMINUM ALLOY 7075-T6

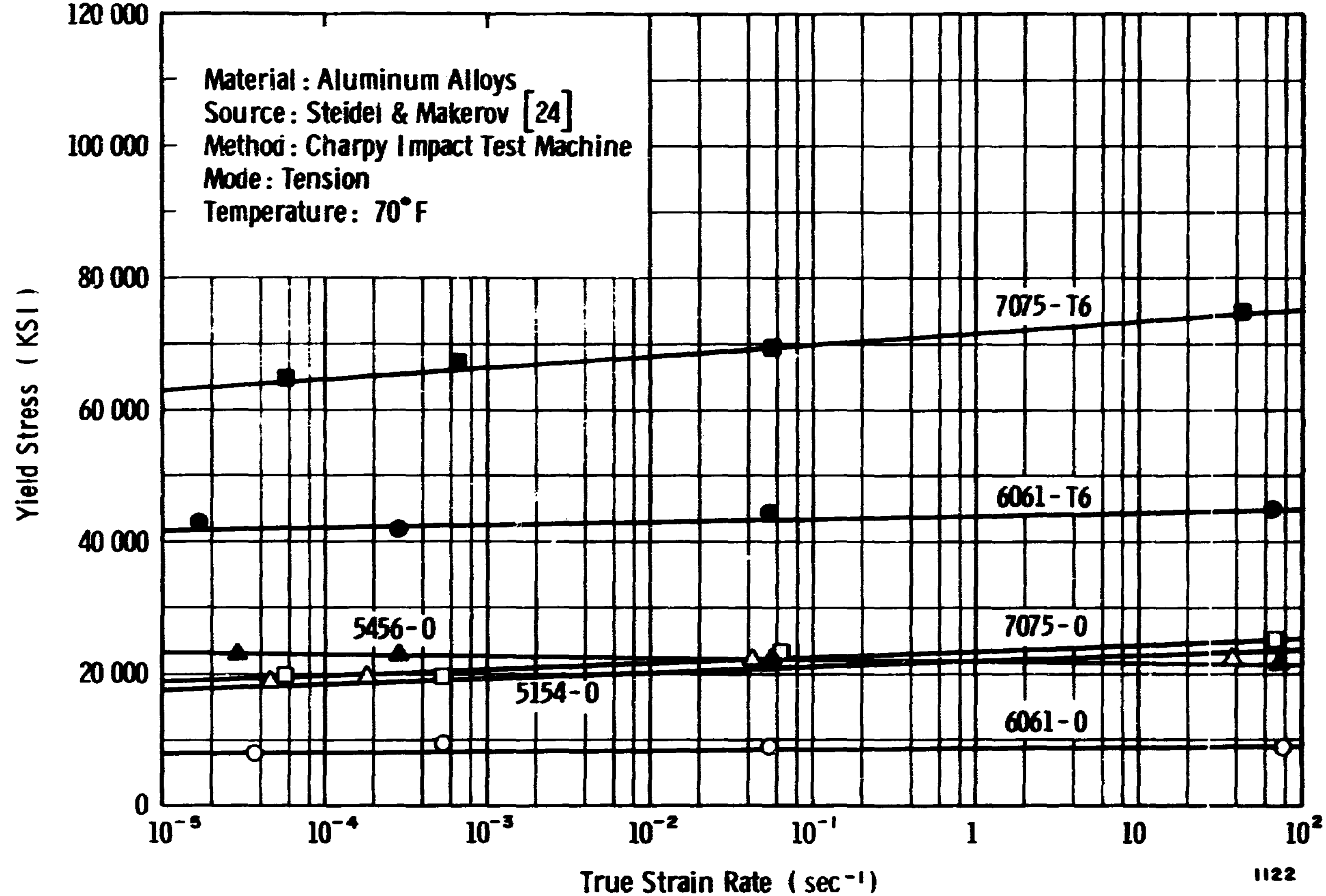

FIGURE 13. SEVERAL ALUMINUM ALLOYS

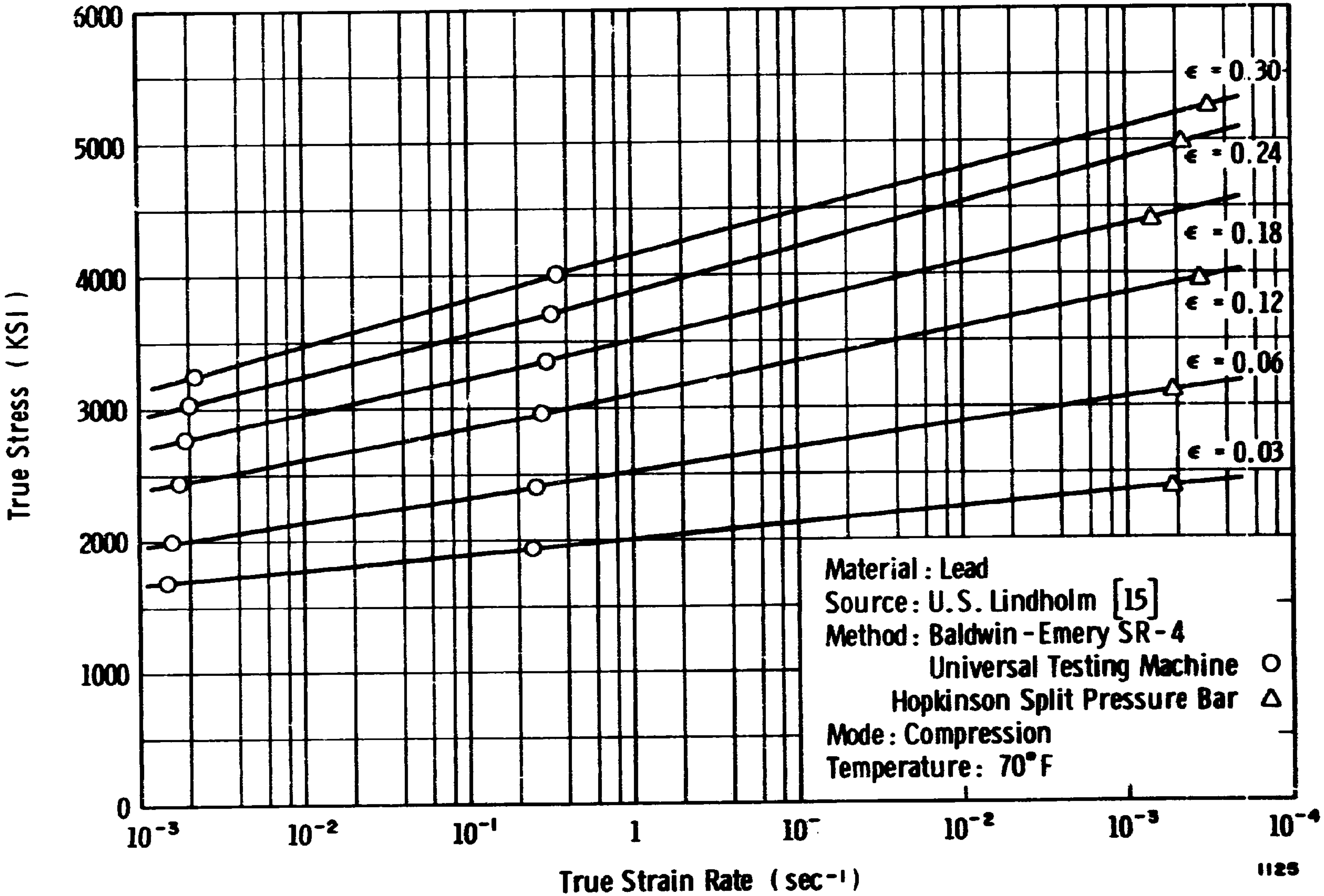

FIGURE 14. COMMERCIAL PURITY LEAD

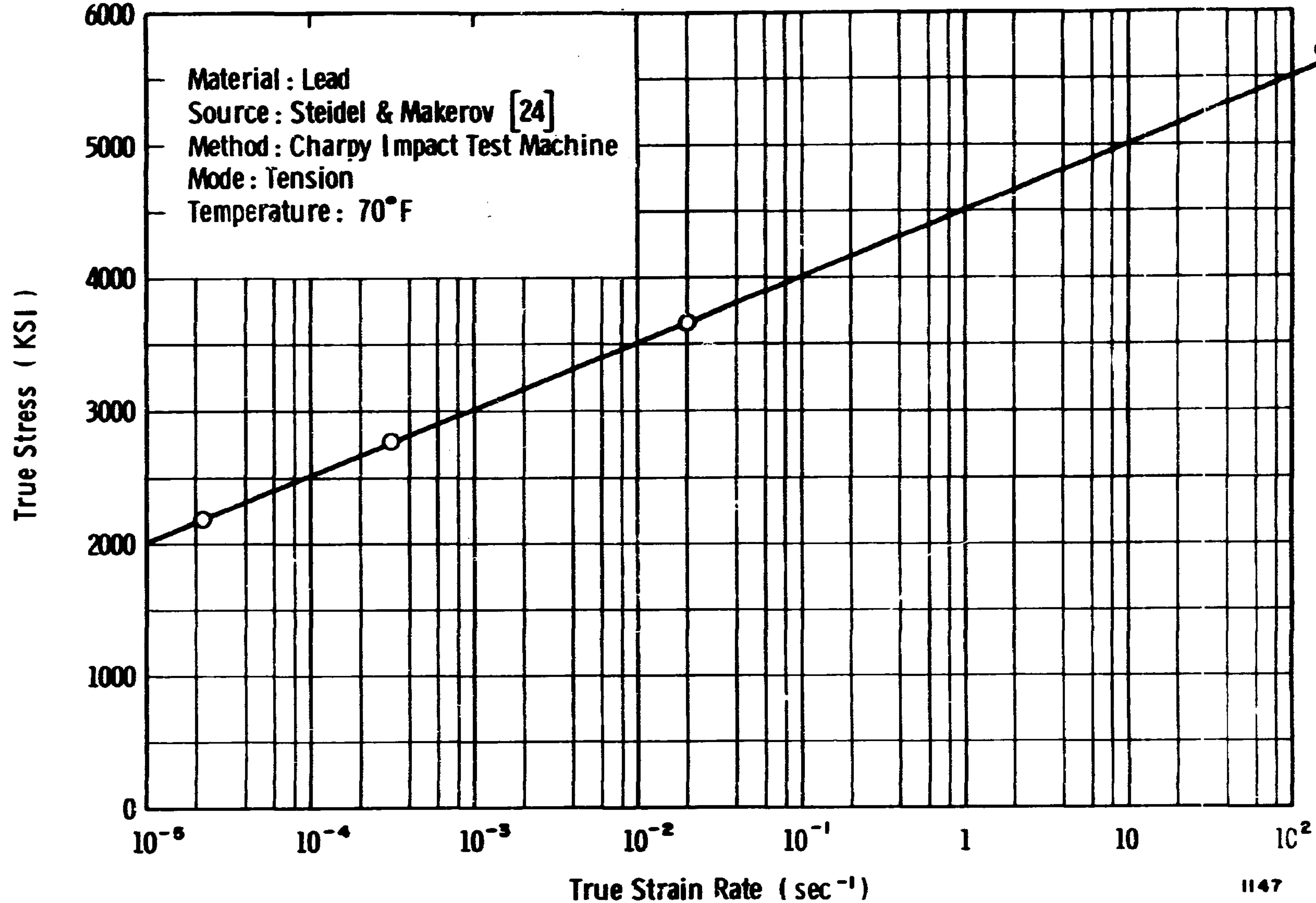

FIGURE 15. LEAD

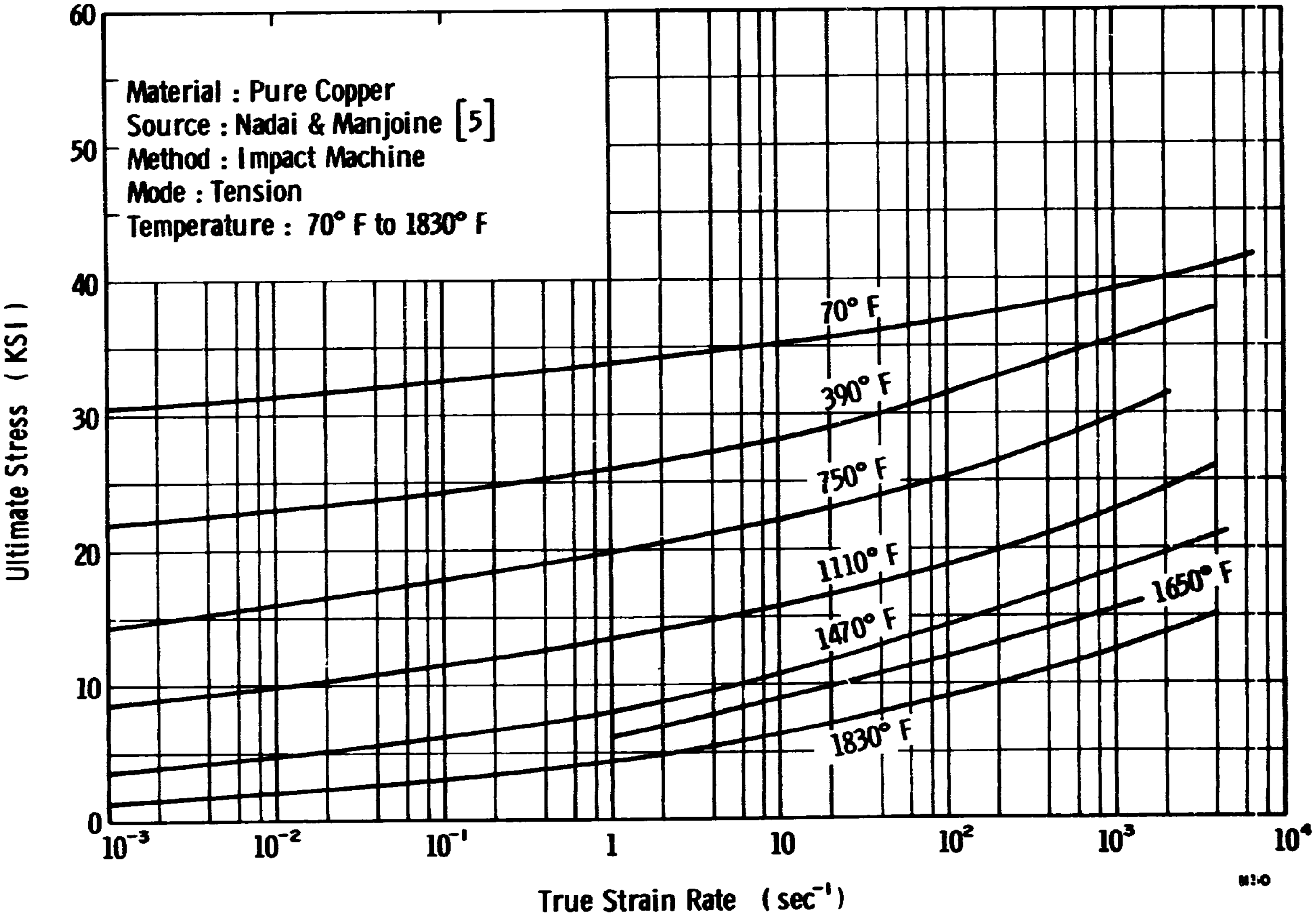

FIGURE 16. COPPER

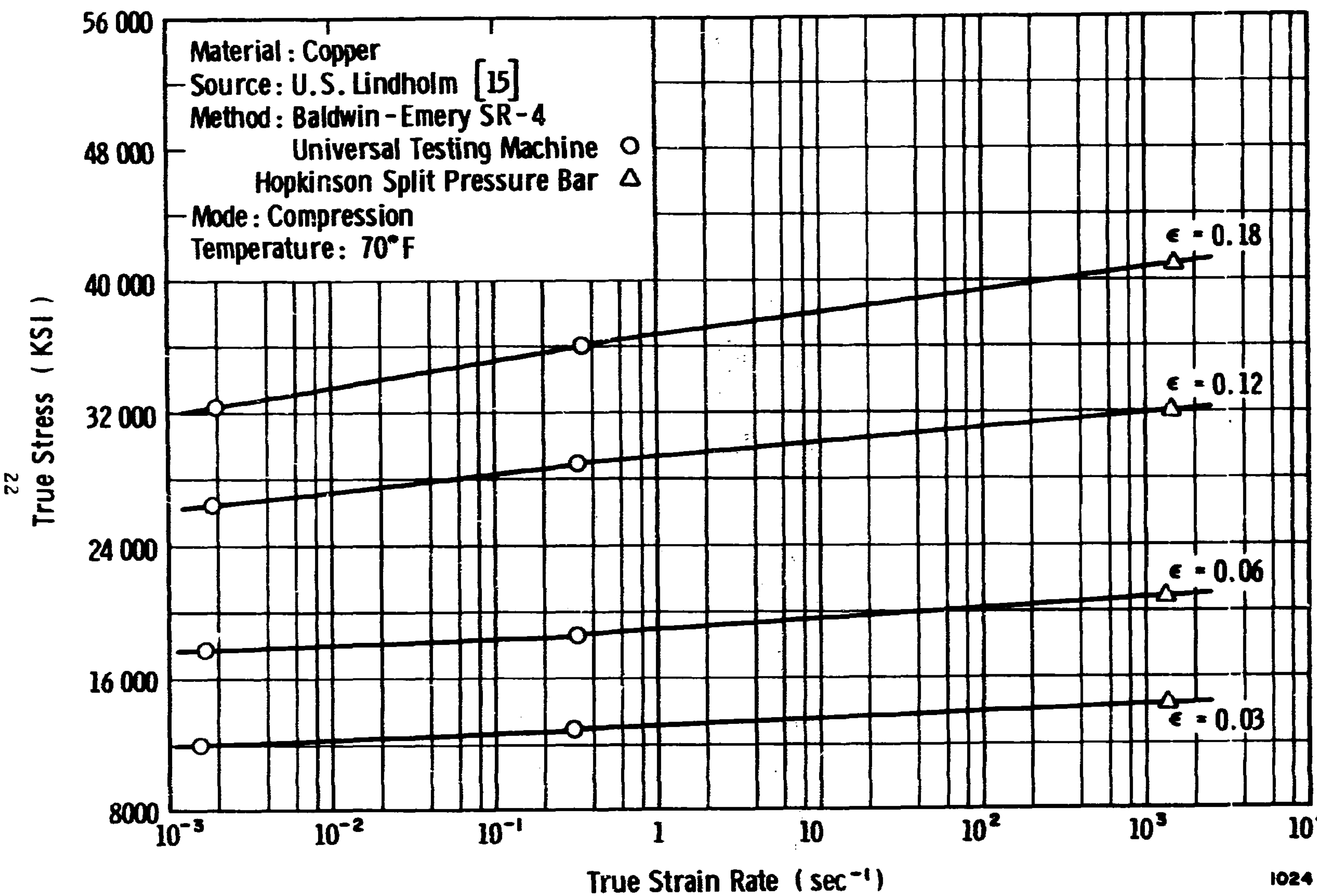

FIGURE 17. COPPER (OFHC)

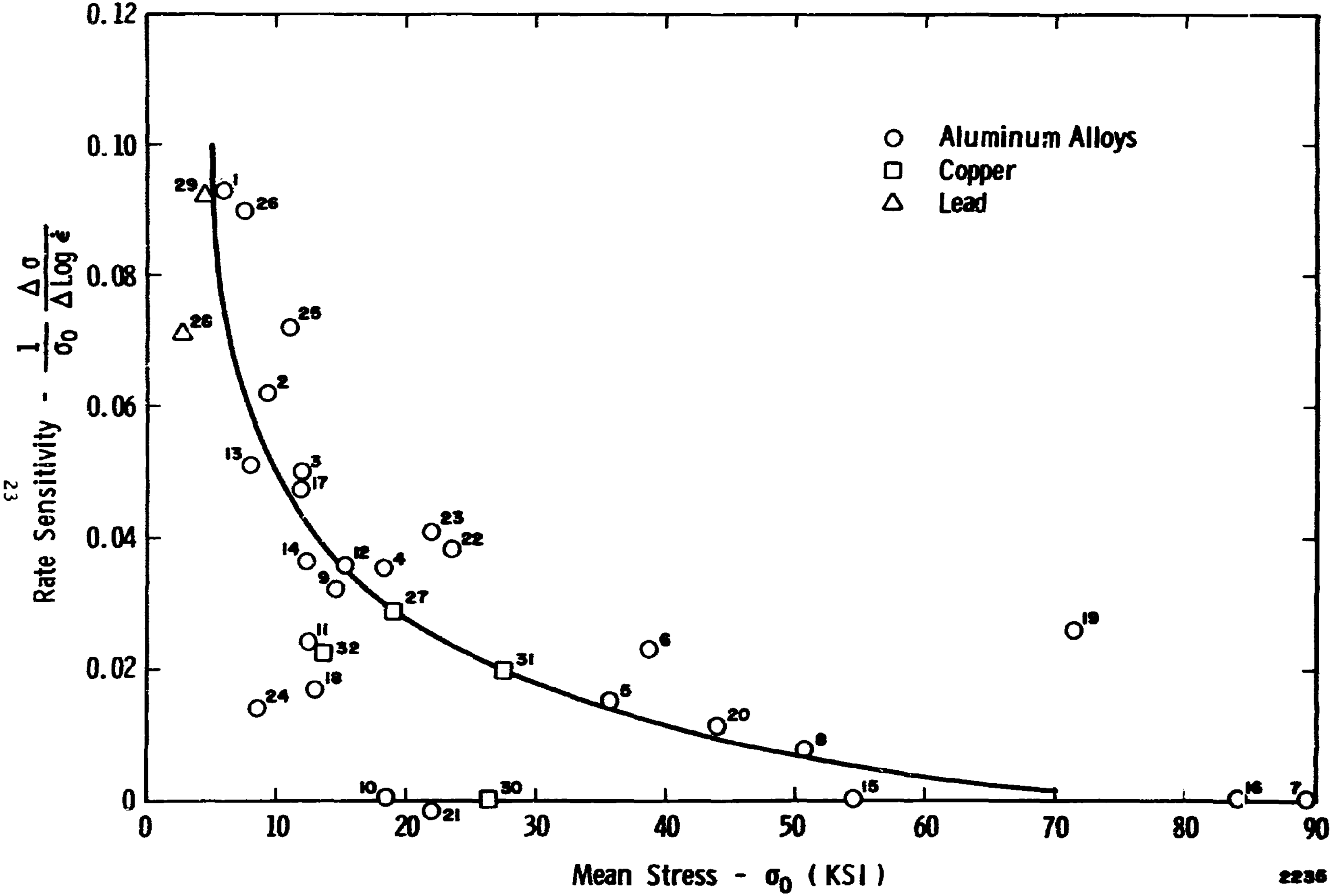

FIGURE 18. RATE SENSITIVITY PARAMETER VS. MEAN FLOW STRESS FOR ALUMINUM ALLOYS, COPPER AND LEAD. NUMBER BY EACH DATA POINT IS REFERENCED TO TABLE I.

TABLE I.
REFERENCES FOR FIGURE 18.

ALUMINUM

No.	Source	Ref.	Alloy	Strain
1	Holt, et. al.	22	99.999%	0.06
2	Holt, et. al.	22	1060-0	0.06
3	Holt, et. al.	22	1100-0	0.06
4	Holt, et. al.	22	6061-0	0.06
5	Holt, et. al.	22	2024-0	0.06
6	Holt, et. al.	22	7075-0	0.06
7	Holt, et. al.	22	7075-T6	0.06
8	Holt, et. al.	22	6061-T6	0.06
9	Alder, Phillips	7	99.5%	0.10
10	Kolsky, Douch	32	97.8 Al, 0.9 Mg, 0.9Si	0.06
11	Kolsky, Douch	32	99.5%	0.06
12	Hockett	8	1100-0	0.10
13	Lindholm, Yeakley	33	99.995	0.06
14	Lindholm	15	1100-0	0.06
15	Lindholm, Yeakley	34	6061-T6	0.06
16	Lindholm, et. al.	1	7075-T6	0.06
17	Chiddester, Malvern	23	1100-F	0.05
18	Schultz	35	1100-0	0.20
19	Stiedel, Makerov	24	7075-T6	Yield
20	Stiedel, Makerov	24	6061-T6	Yield
21	Stiedel, Makerov	24	5456-0	Yield
22	Stiedel, Makerov	24	7075-0	Yield
23	Stiedel, Makerov	24	5154-0	Yield
24	Stiedel, Makerov	24	6061-0	Yield
25	Hauser	16	99.997%	0.01
26	Karnes, Ripperger	36	99.995	

OTHER FCC METALS

No.	Source	Ref.	Alloy	Strain
27	Lindholm	15	Cu (OFHC)	0.06
28	Lindholm	15	Pb	0.06
29	Stiedel, Makerov	24	Pb	Yield
30	Alder, Phillips	7	Cu	0.10
31	Kolsky, Douch	32	Cu (99.9%)	0.06
32	Baker, Yew	37	Cu	0.16

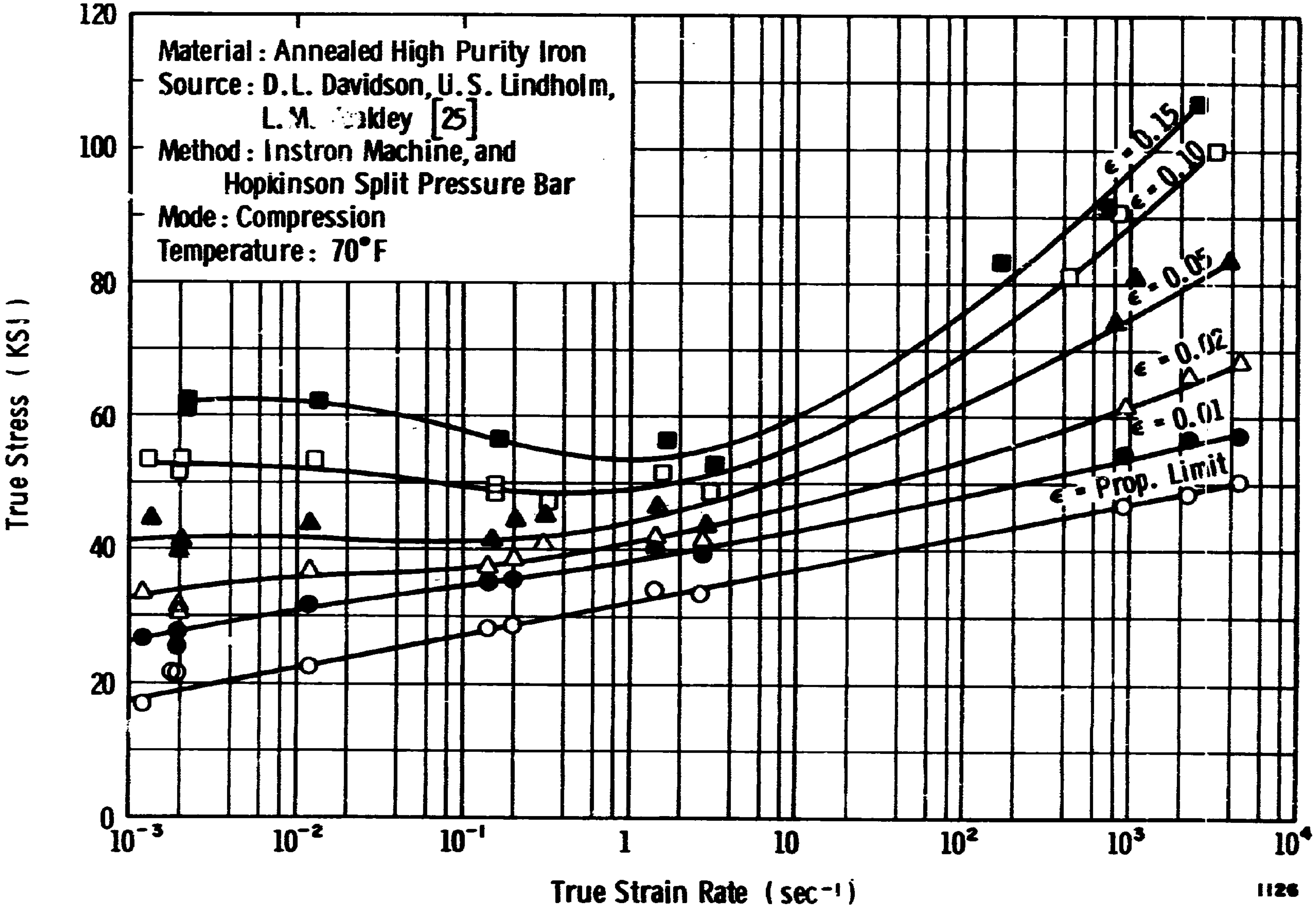

FIGURE 19. HIGH PURITY IRON

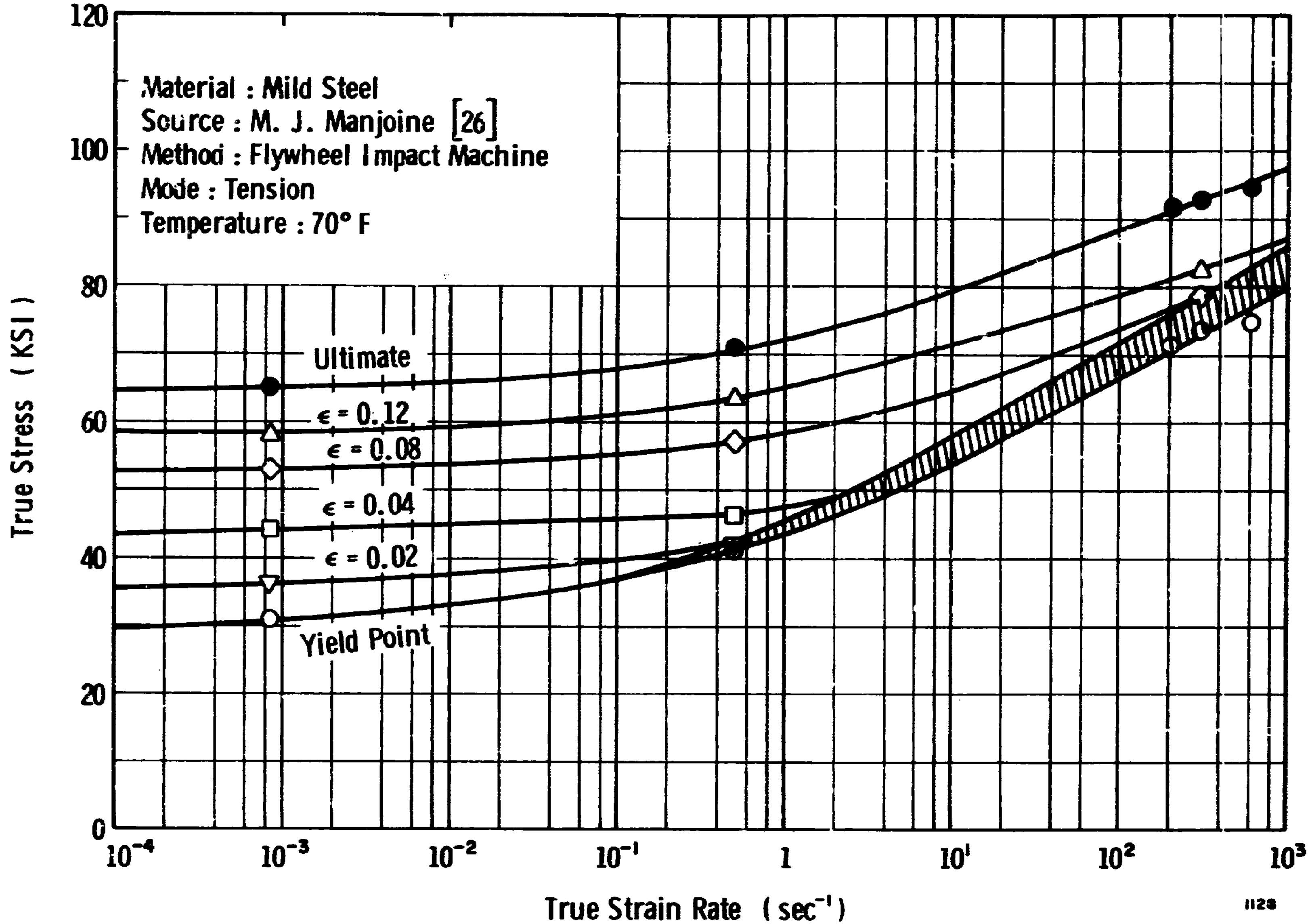

FIGURE 20. MILD STEEL AT 70°F

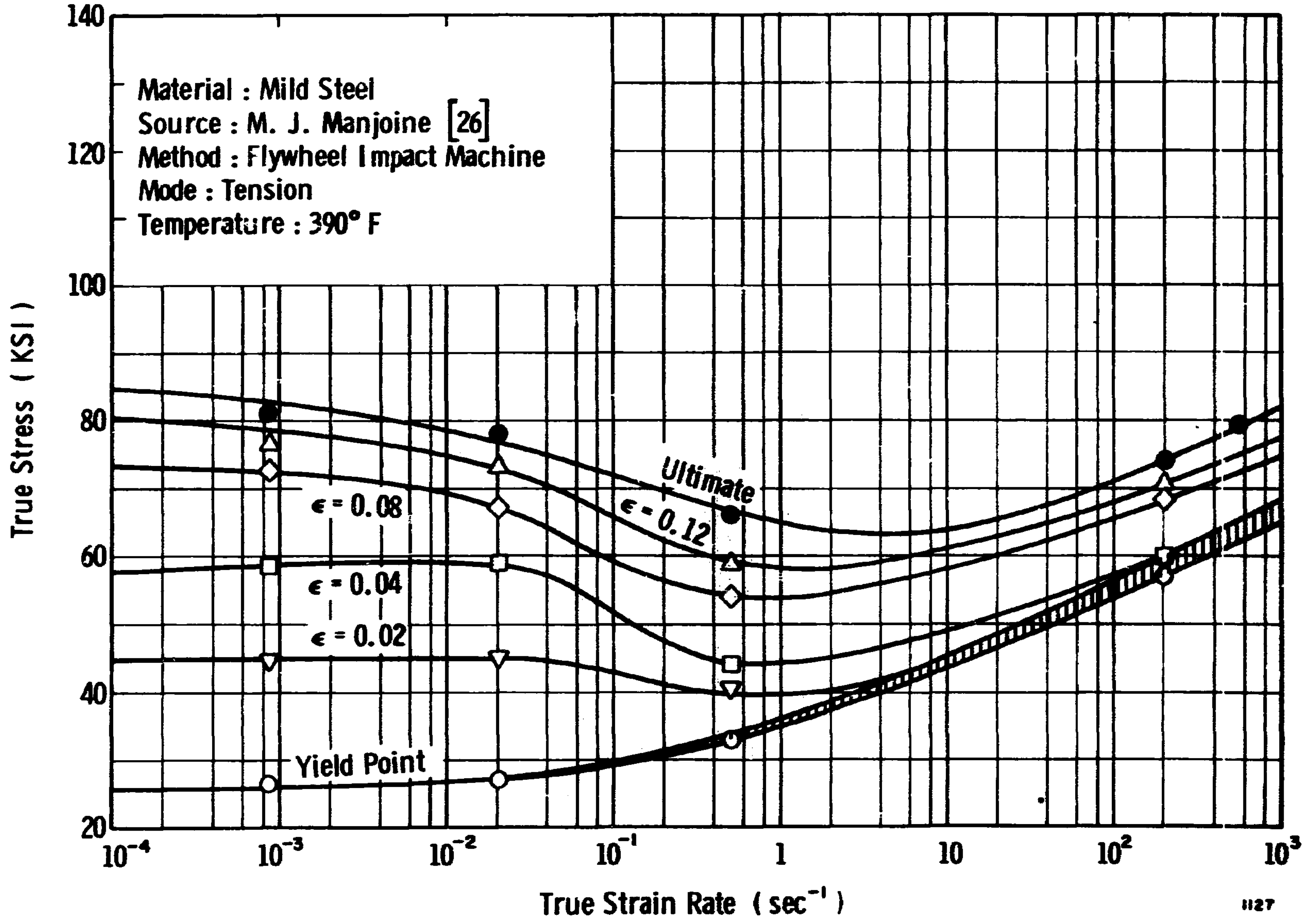

FIGURE 21. MILD STEEL AT 390°F

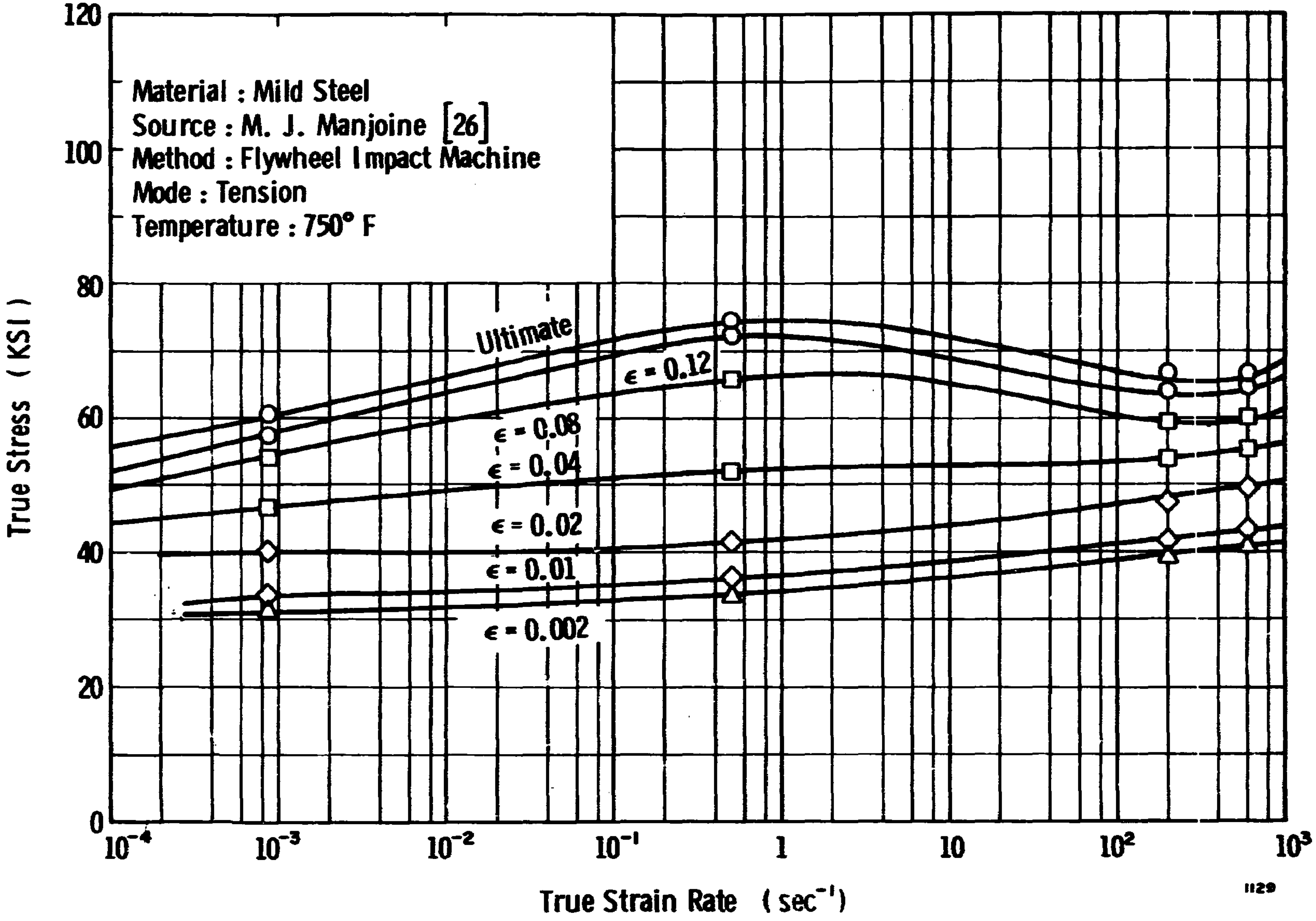

FIGURE 22. MILD STEEL AT 750°F

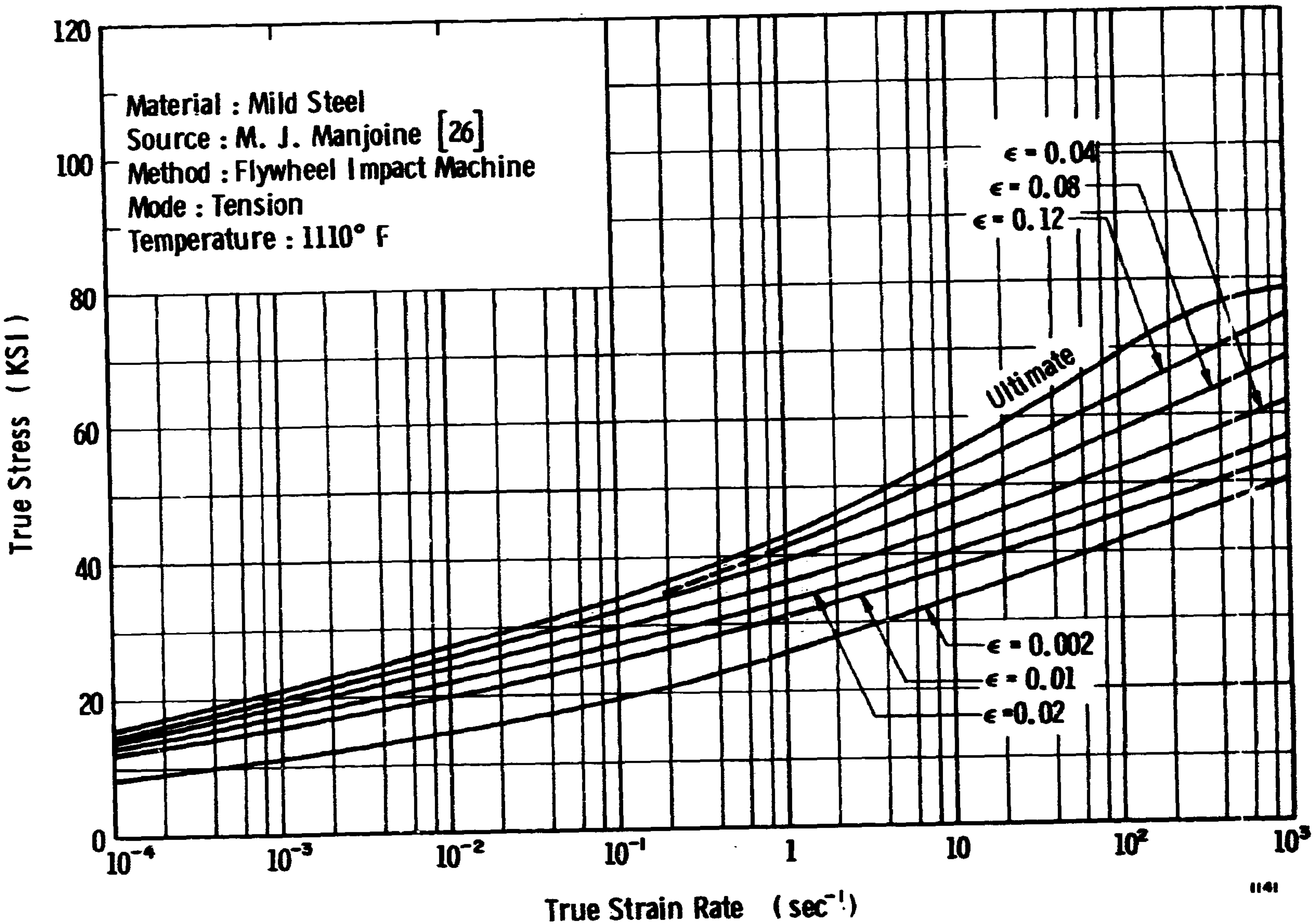

FIGURE 23. MILD STEEL AT 1110°F

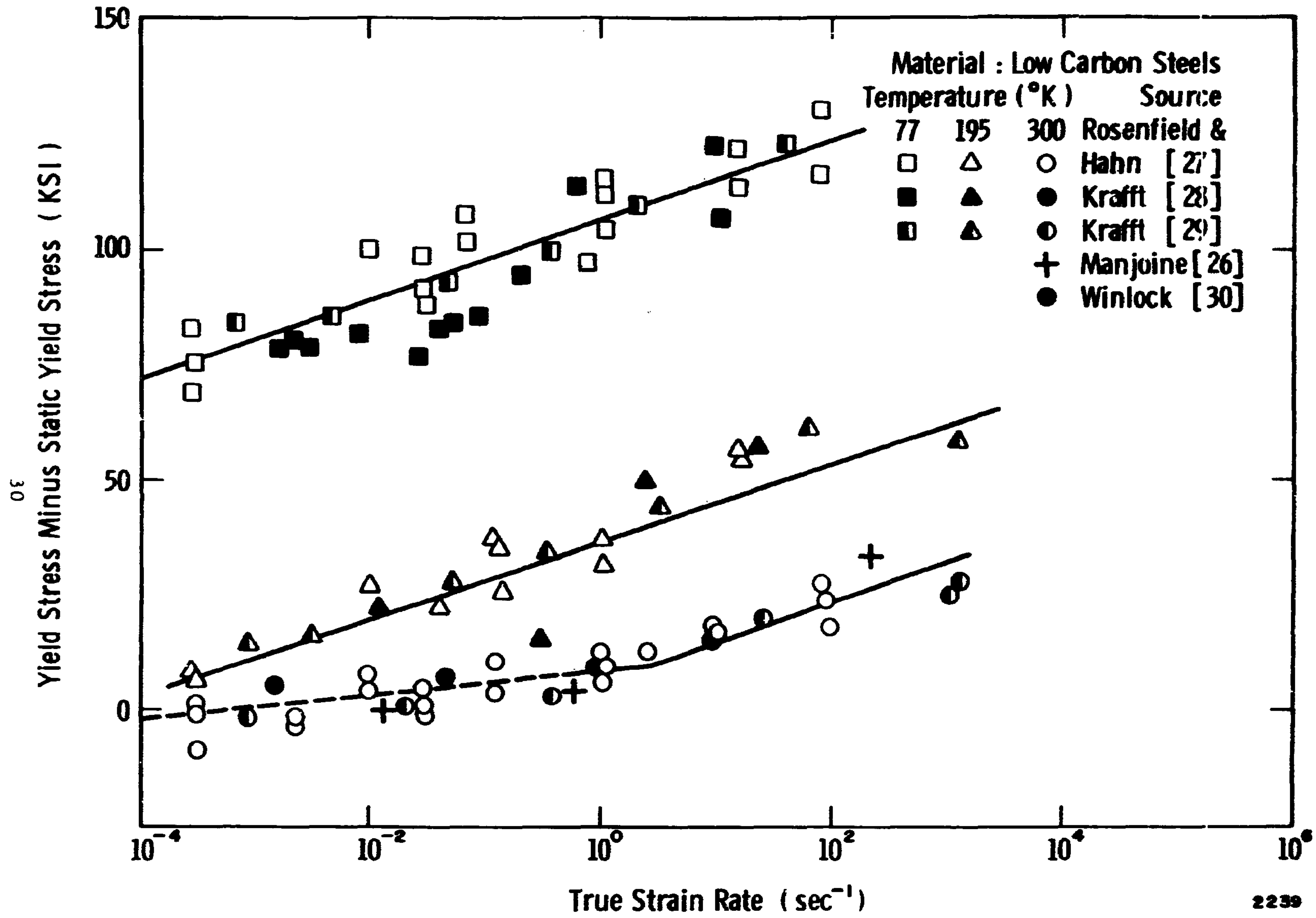

FIGURE 24. SUMMARY OF SEVERAL LOW CARBON STEELS AFTER REF. 27

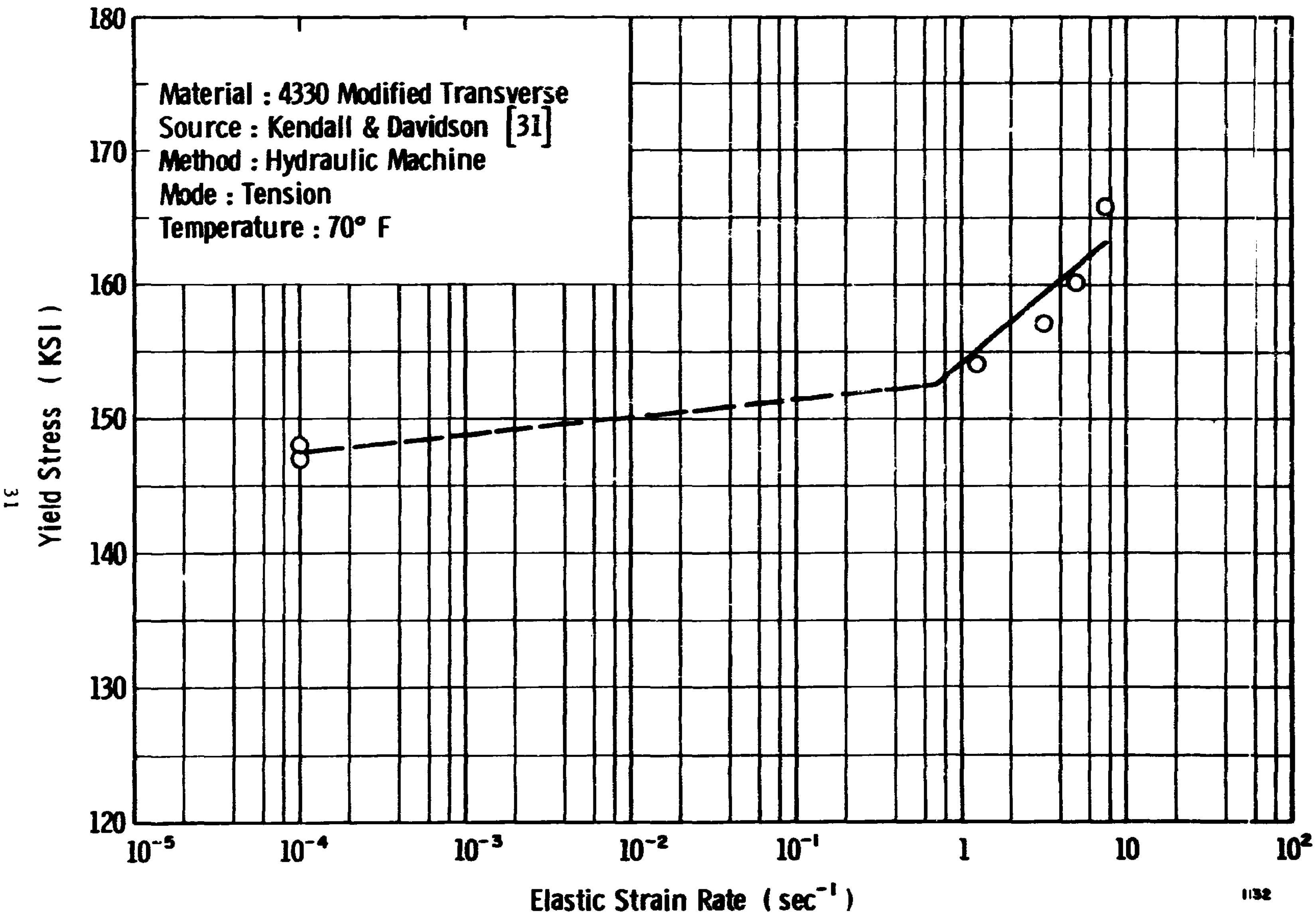

FIGURE 25. A MODIFIED 4330 STEEL CUT IN TRANSVERSE DIRECTION FROM A GUN TUBE FORGING

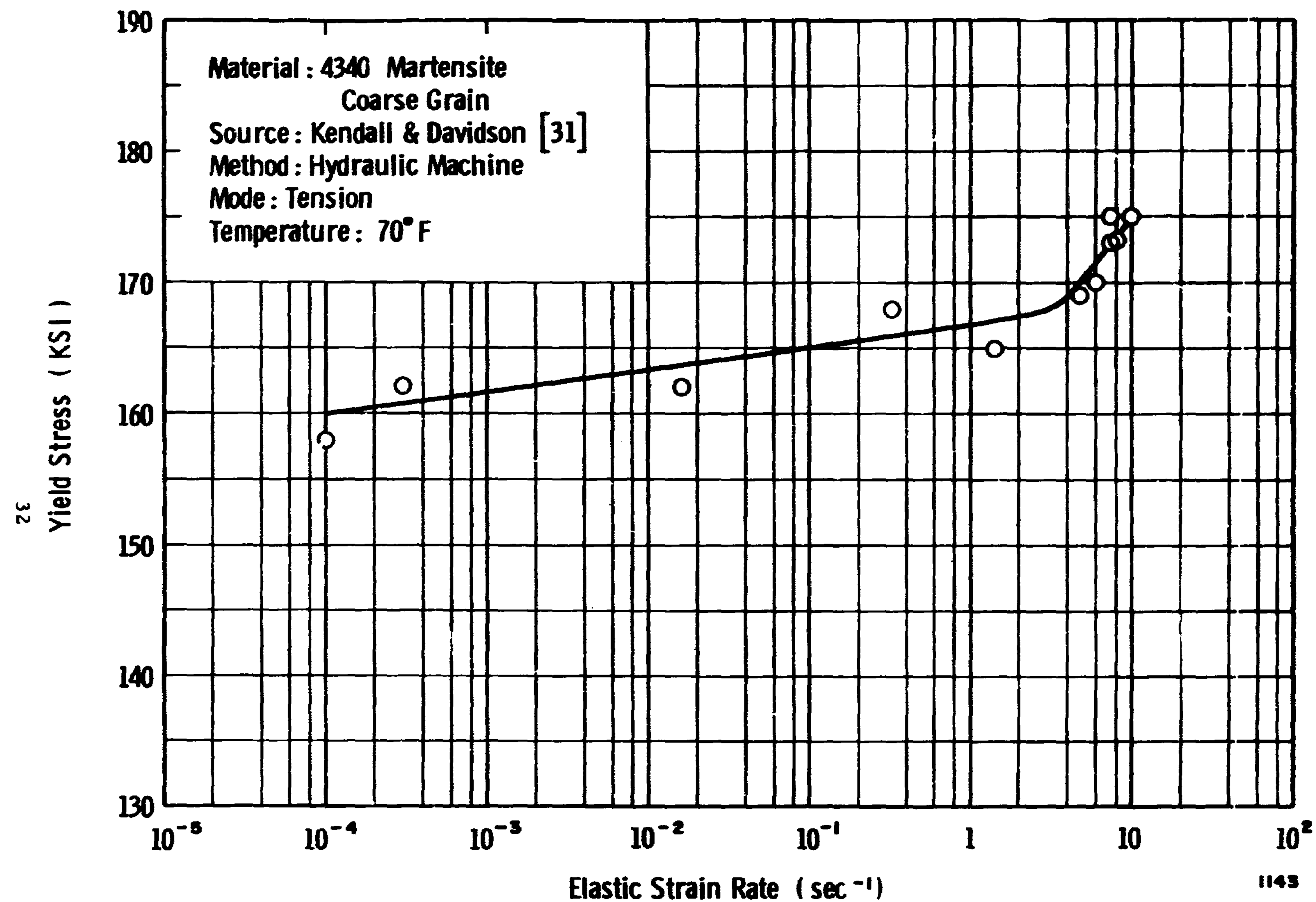

FIGURE 26. 4340 COARSE GRAINED, MARTENSITE STEEL

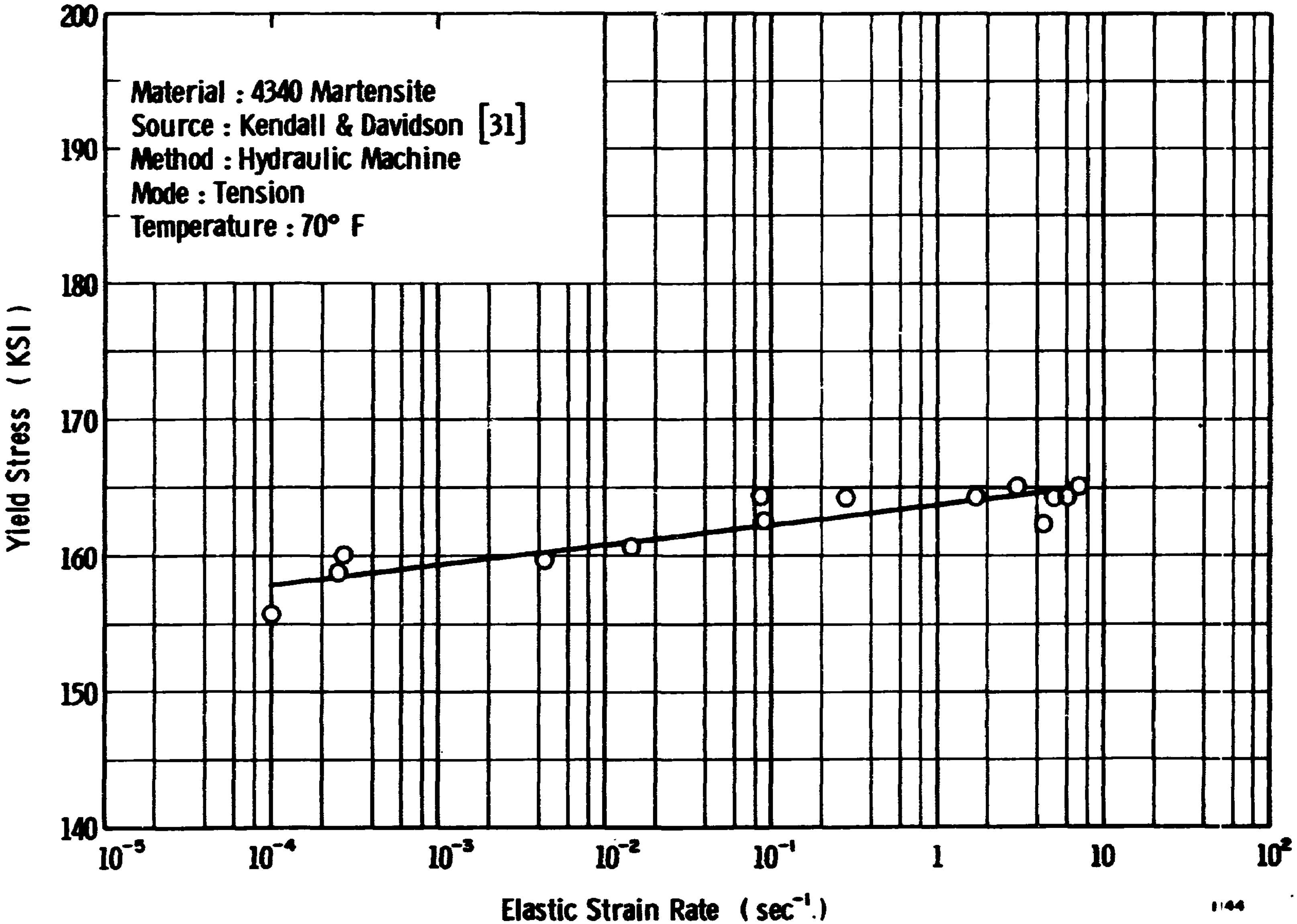

FIGURE 27. 4340 FINE GRAINED, MARTENSITE STEEL

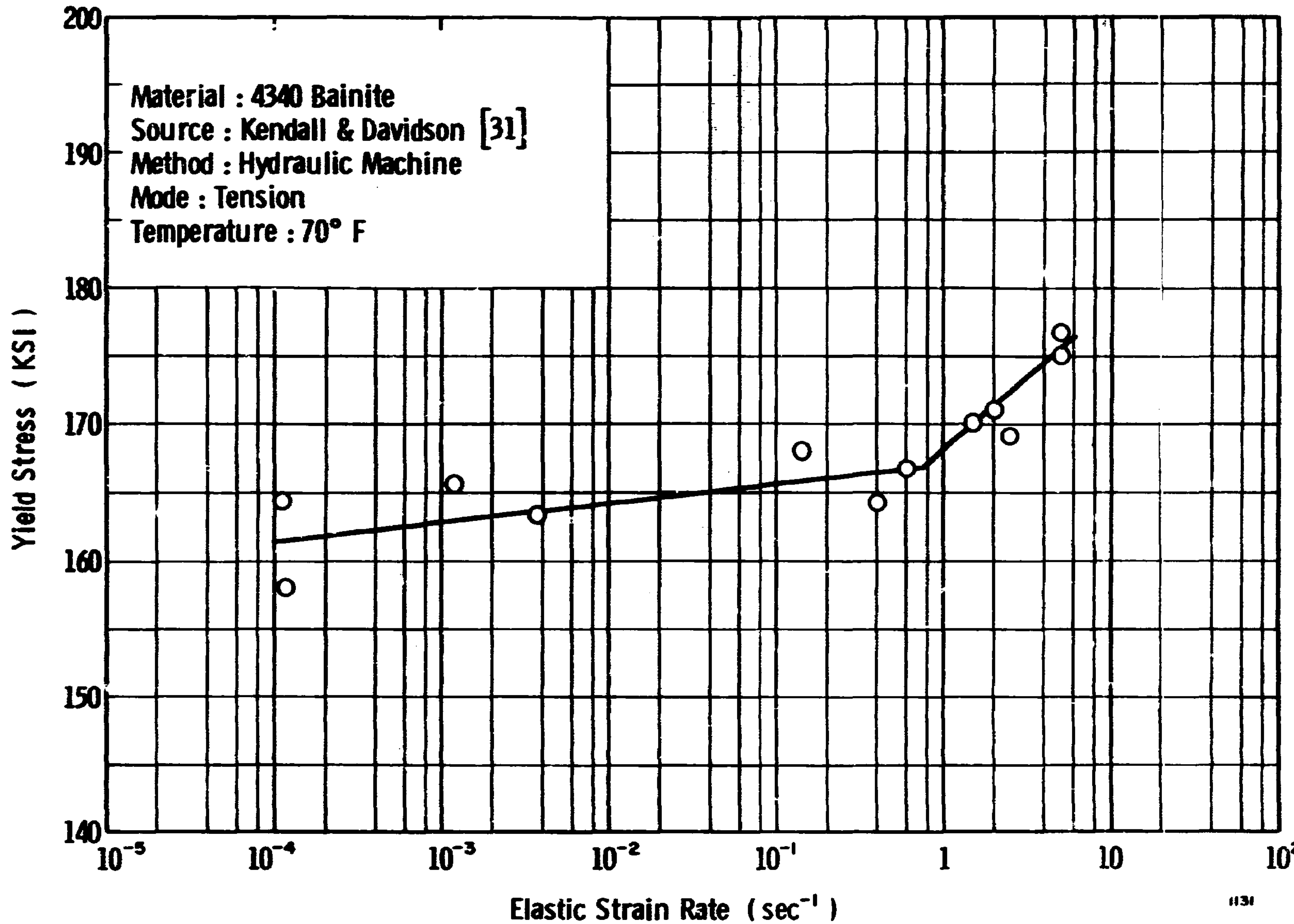

FIGURE 28. 4340 BAINITE

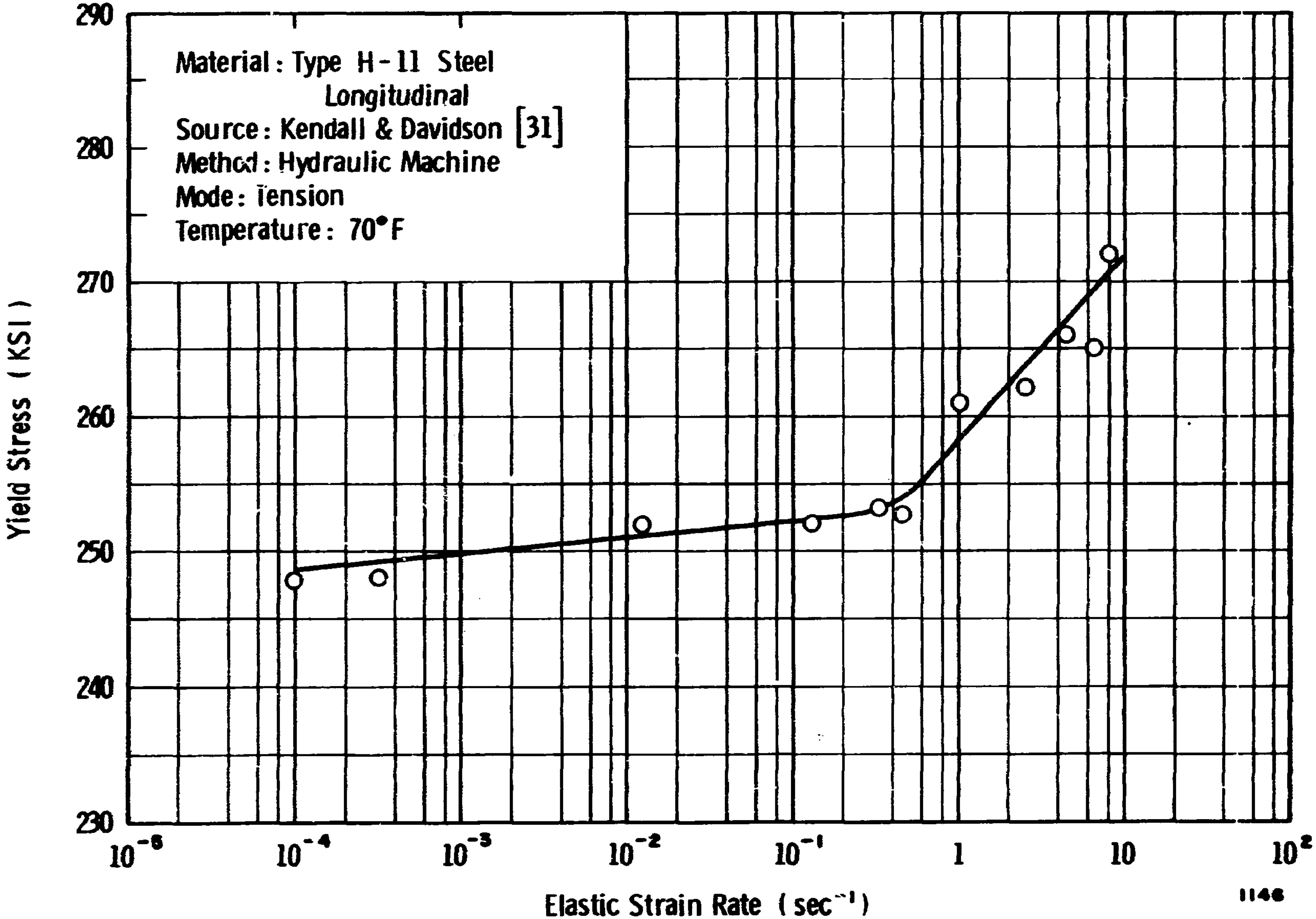

FIGURE 29. TYPE H-11 HIGH CHROMIUM STEEL

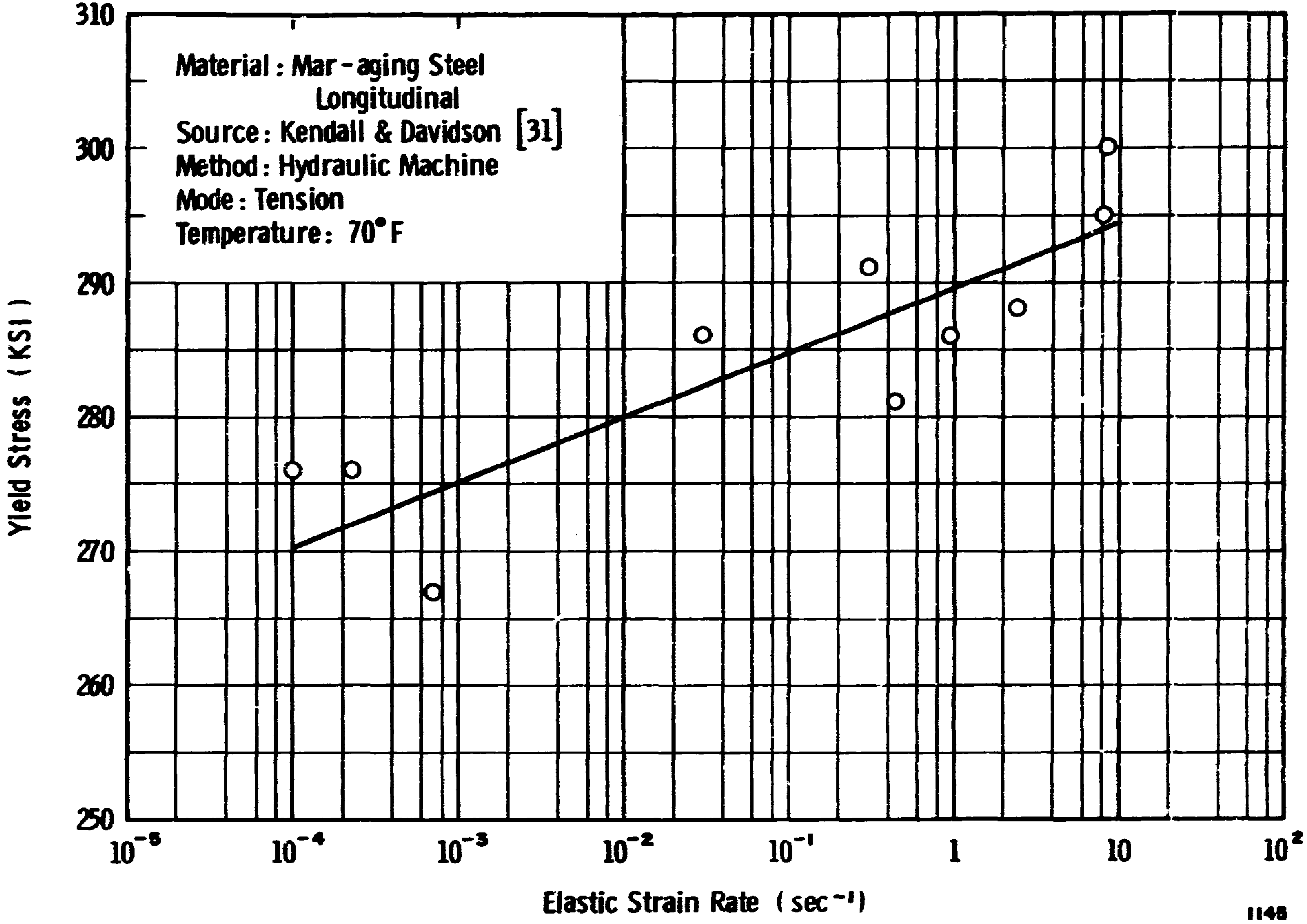

FIGURE 30. MAR-AGING STEEL, LONGITUDINAL

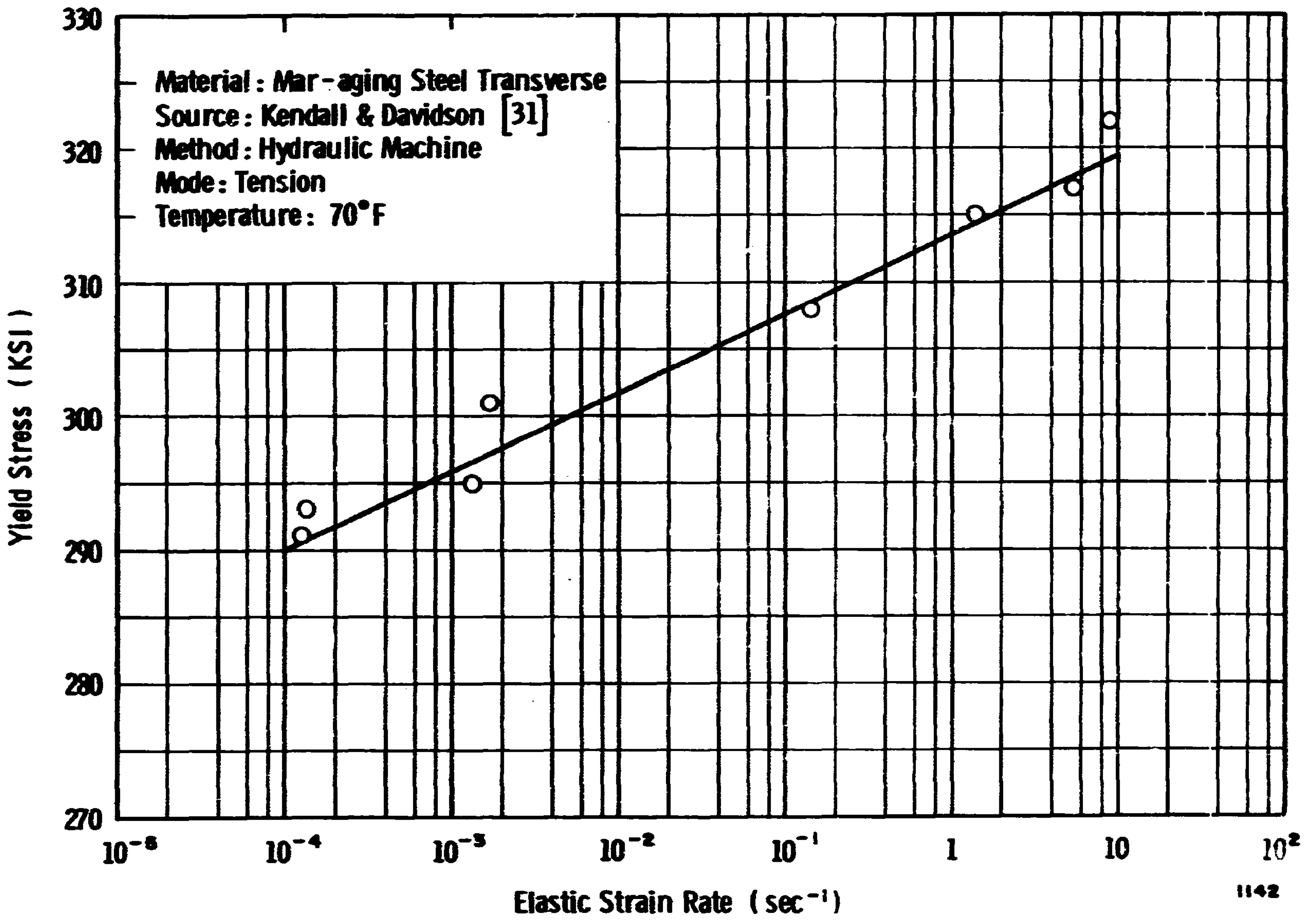

FIGURE 31. MAR-AGING STEEL, TRANSVERSE

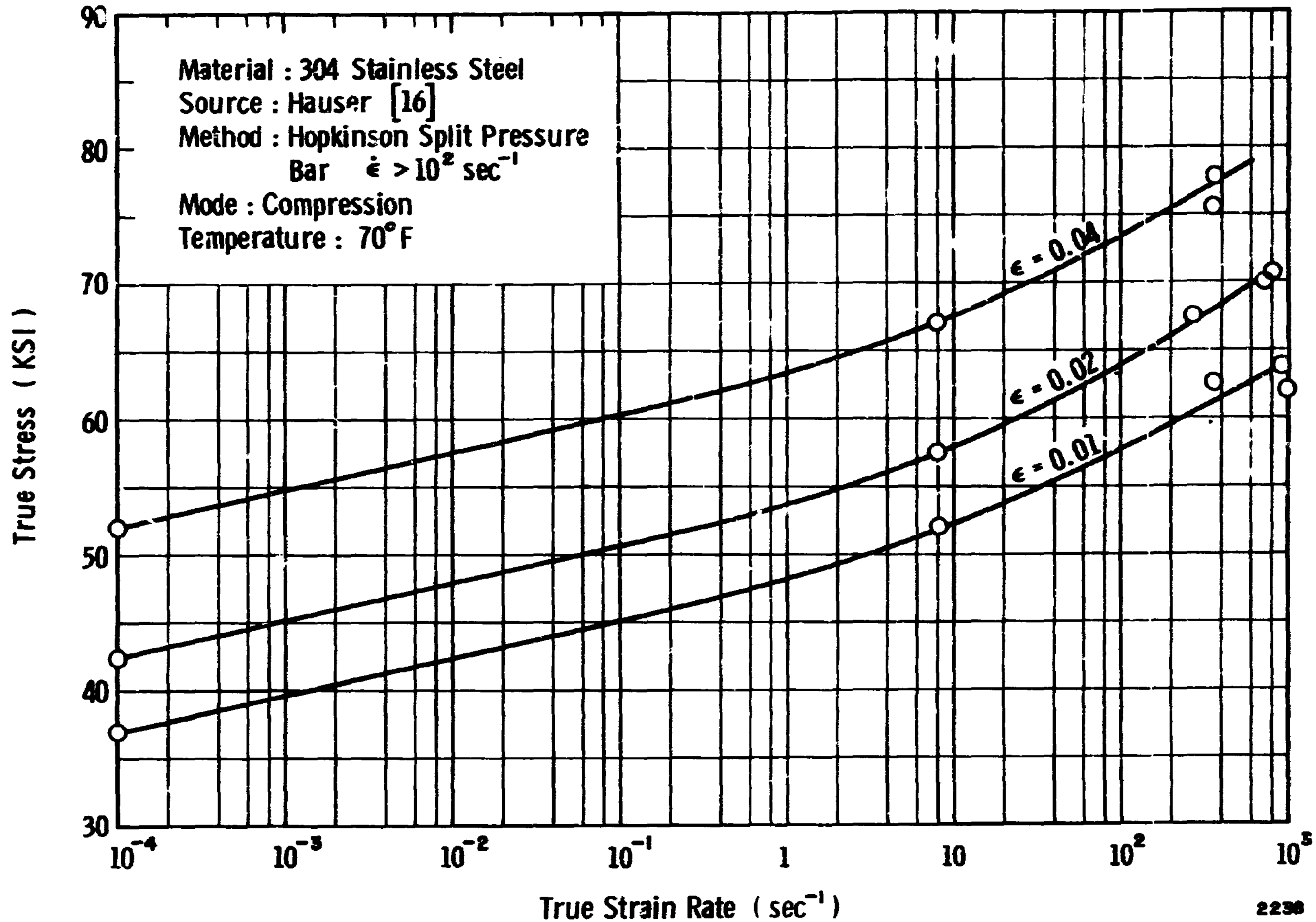

FIGURE 32. TYPE 304 STAINLESS STEEL

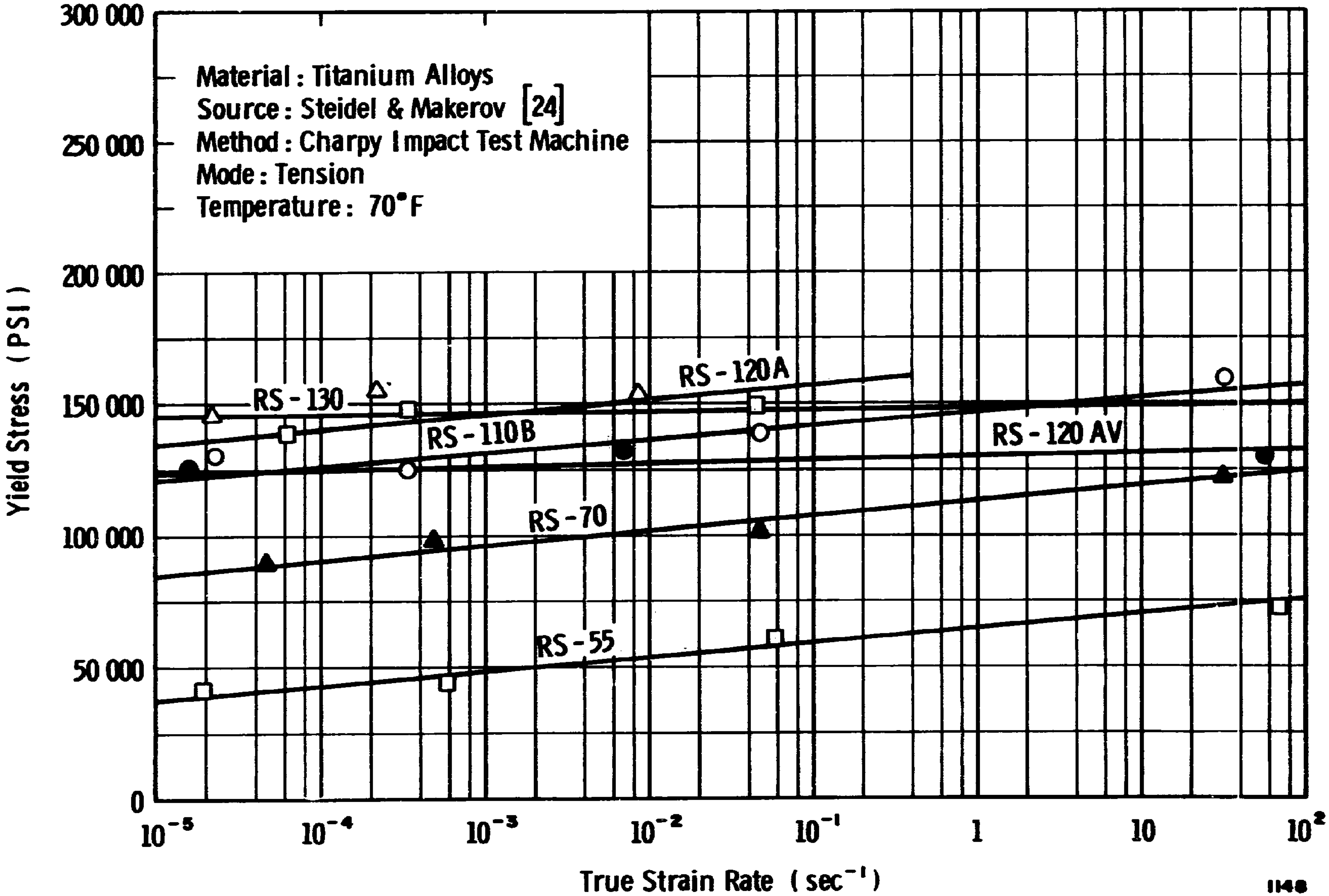

FIGURE 33. YIELD STRESS OF SEVERAL TITANIUM ALLOYS

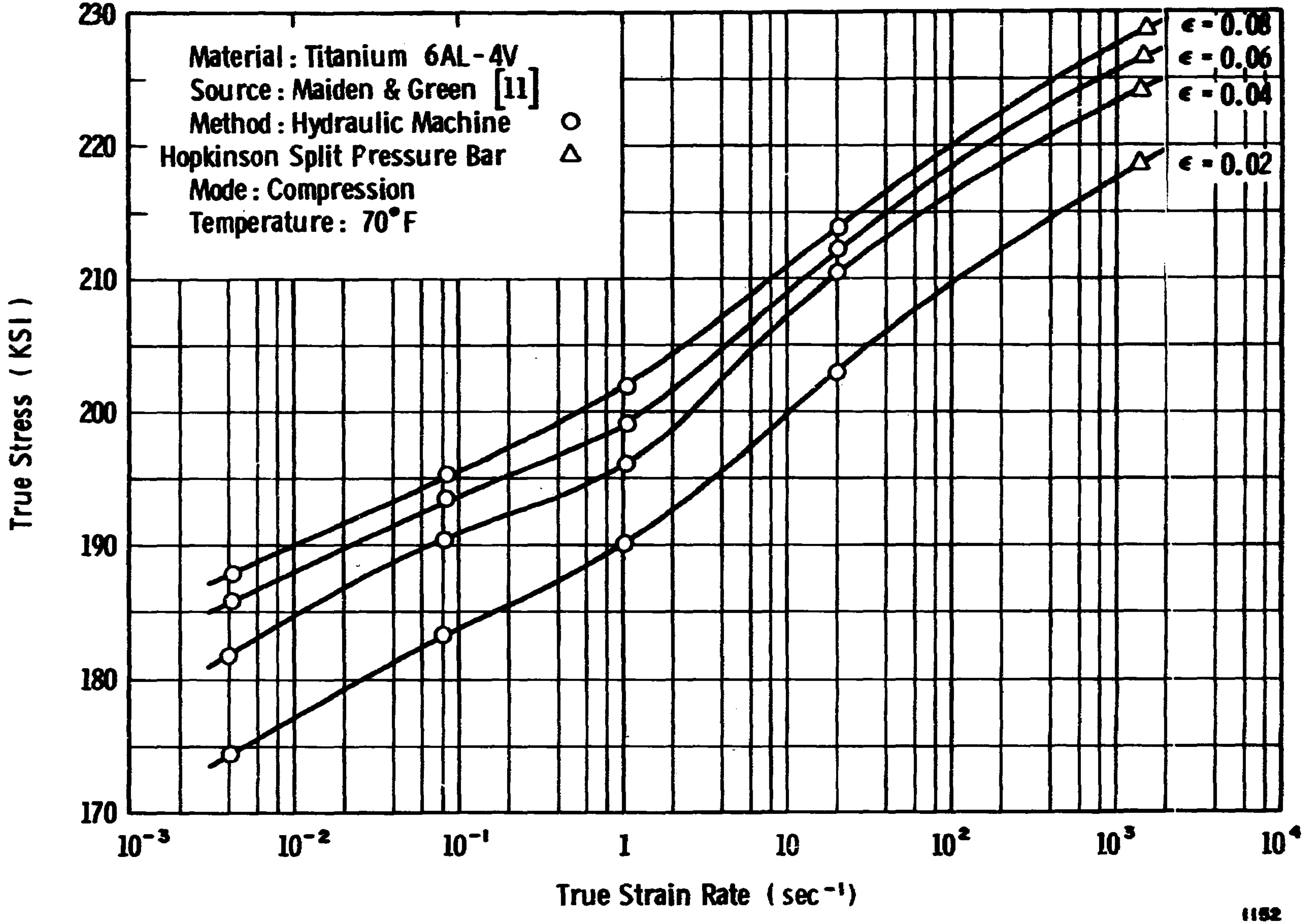

FIGURE 34. TITANIUM 6AL-4V

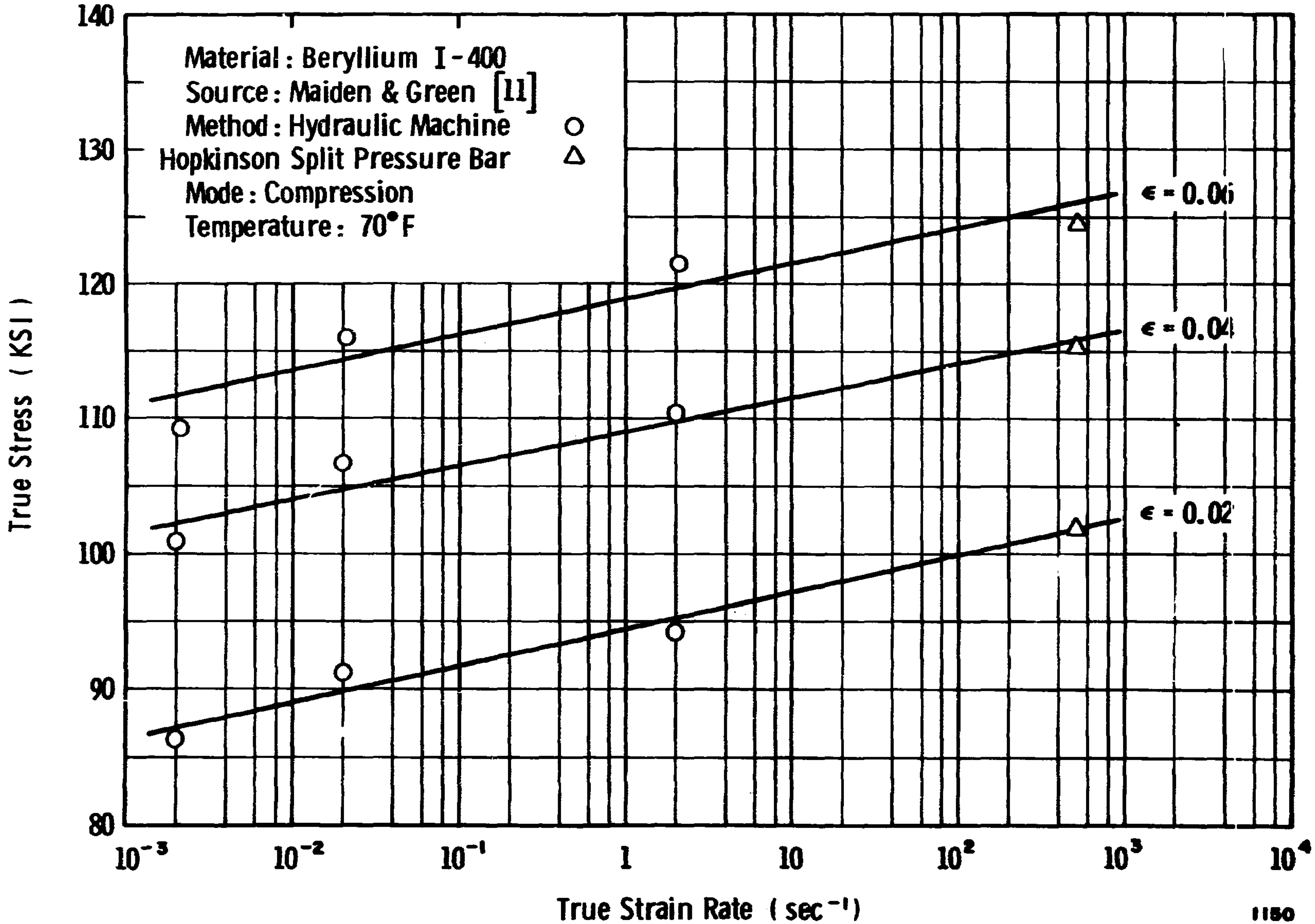

FIGURE 35. BERYLLIUM I-400

SECTION IV

DISCUSSION

The data presented illustrate the range in rate sensitivity to be expected from a wide range of metals and alloys. There are two observations to be made regarding the consistency of the data. First, data obtained by a single investigator for a given material appear to be very consistent over the wide range in rates, even though two or sometimes three different test techniques were employed. This is important in showing that the highest rate data, obtained under conditions where wave propagation effects always lead to some uncertainty, are consistent with data obtained at low rates where equilibrium conditions are known to prevail and accuracy is more easily determined. Second, where comparisons can be made there is generally good agreement between the results of two or more different investigators. Figures 18 and 24 illustrate this to some extent for aluminum alloys and steels. Small differences in impurity or alloy content between materials of the same nominal designation can make quantitative comparisons of the later type difficult. For instance, in the low stress region of Figure 18, it is observed that small changes in alloy content lead to large changes in the apparent rate sensitivity.

The aforementioned indications of consistency lead to another general observation to the effect that we now appear to have at hand the capability to generate high strain rate data in the range considered with accuracy at least sufficient for engineering purposes. With the acquisition of such data, we should now be able to determine for any given material whether or not higher allowable stresses can be used in design situations where dynamic loads are governing.

A final observation is that extrapolation of the available data beyond the range of strain rate or of temperature at which the tests were performed is not recommended. The detailed mechanisms controlling the plastic flow of metals are very complex and there is no assurance, and indeed little likelihood, that the same mechanisms are operative over the whole range of conditions encountered. The detailed study of deformation mechanisms is a major area of current effort so that perhaps in the future our predictive capacity will be better. However, as a rule, with increasing temperature the rate sensitivity increases. For instance, while 7075-T6 aluminum is not rate sensitive at room temperature (Figure 12), above 300°F the rate sensitivity becomes appreciable[1]. Similarly, at strain rates above 1000 in/in/sec,

what little evidence there is indicates that the rate sensitivity increases markedly. Some data indicating this for steel are summarized by Rosenfield and Hahn[27]. Similar behavior is observed in aluminum by Hauser[16]. Obviously, further work and documentation is required.

SECTION V

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Department of Mechanical Sciences Southwest Research Institute San Antonio, Texas	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
A Survey of Rate Dependent Strength Properties of Metals

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report - July 1966 to November 1968

5. AUTHOR(S) (First name, middle initial, last name)
U. S. Lindholm
R. L. Bessey

6. REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO. OF REFS
April 1969	47	47

8a. CONTRACT OR GRANT NO AF 33(615)-5338	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 3
b. PROJECT NO. 7351	
c. Task No. 735106	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	AFML-TR-69- 119

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Metals and Ceramics Division Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

The data available from the open literature concerning the effect of strain rate on the strength properties of metals have been collected and are presented in graphical form. The range in strain rate included is from approximately 10^{-4} in/in/sec to 10^3 in/in/sec. While most of the strength data has been obtained at room temperature, some elevated temperature data is available also. It can be seen that most information has been obtained on the aluminum and ferrous alloys.

This collection of data should serve as a useful source for those requiring high strain-rate information for design applications and as an indication where further work is required.

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DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Metals						
Mechanical Properties						
Strain-Rate Effects						

END